High Energy Physics

Overview

The High Energy Physics (HEP) program's mission is to understand how the universe works at its most fundamental level by discovering the elementary constituents of matter and energy, probing the interactions between them, and exploring the basic nature of space and time.

Our current understanding of the elementary constituents of matter and energy is captured in what is called the Standard Model of particle physics. It describes the elementary particles that comprise ordinary matter and the forces that govern them with very high precision. However, recent observations that are not explained by the Standard Model suggest that it is incomplete and new physics may be discovered by future experiments. Astronomical observations indicate that ordinary matter makes up only about 5% of the universe, the remainder being 70% dark energy and 25% dark matter, both "dark" because they are either nonluminous or unknown. The observation of very small but non-zero masses of the elementary particles known as neutrinos provides further hints of new physics beyond the Standard Model.

A world-wide program of particle physics research is underway to discover what lies beyond the Standard Model. To guide U.S. investments, the U.S. particle physics community developed a long-term strategic plan through a multi-year process that culminated in the May 2014 report of the Particle Physics Project Prioritization Panel (P5), "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context."[a] The P5 report was unanimously approved by the High Energy Physics Advisory Panel (HEPAP) to serve the DOE and National Science Foundation (NSF) as the ten-year strategic plan for U.S. high energy physics in the context of a 20-year global vision. The P5 report identified five intertwined science drivers of particle physics that provide compelling lines of inquiry with great promise for discovery:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

The HEP program enables scientific discovery through three experimental frontiers of particle physics research aligned with three HEP subprograms:

- Energy Frontier, where researchers accelerate particles to the highest energies ever made by humanity and collide them to produce and study the fundamental constituents of matter. This requires some of the largest machines ever built. The Large Hadron Collider (LHC) at the European Organization for Nuclear Research, known as CERN, is 17 miles in circumference and accelerates and collides high-energy protons, while sophisticated detectors, some the size of apartment buildings, observe newly produced particles that provide insight into fundamental forces of nature and the conditions of the early universe.
- Intensity Frontier, where researchers use a combination of intense particle beams and highly sensitive detectors to make extremely precise measurements of particle properties, study some of the rarest interactions predicted by the Standard Model, and search for new physics. Measurements of the mass and other properties of neutrinos may have profound consequences for understanding the evolution and ultimate fate of the universe.
- Cosmic Frontier, where researchers use naturally occurring cosmic particles and phenomena to reveal the nature of dark matter, understand the cosmic acceleration caused by dark energy and inflation, infer certain neutrino properties, and explore the unknown. The highest-energy particles ever observed have come from cosmic sources, and the ancient light from the early universe and distant galaxies allows the distribution of dark matter to be mapped and perhaps the nature of dark energy and inflation to be unraveled. Ultra-sensitive detectors deep underground may glimpse the dark matter passing through Earth. Observations of the cosmic frontier may reveal a universe far stranger than ever thought possible.

[a] High Energy Physics Advisory Panel, Department of Energy. Report of the Particle Physics Project Prioritization Panel (P5). Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context. May 2014. https://science.energy.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_053014.pdf

DOE's support of the Theoretical and Computational Physics and the Advanced Technology Research and Development (R&D) subprograms formulates and enables this program of scientific discovery. The Theoretical and Computational Physics subprogram provides the framework to explain experimental observations and gain a deeper understanding of nature. Theoretical physicists take the lead in the interpretation of a broad range of experimental results and synthesize new ideas as they search for deep connections and develop testable models. Computational Physics provides advanced computing tools and simulations that are necessary for designing, operating, and interpreting experiments across the frontiers and enables discovery research via new techniques. Quantum Information Science (QIS) is a rapidly-developing field involving understanding and manipulating quantum phenomena, and opens prospects for new capabilities in sensing, simulation, and computing. HEP activities will be a part of a larger national effort involving interagency coordination of programs. The Advanced Technology R&D subprogram fosters fundamental research into particle acceleration and detection techniques and instrumentation. These enabling technologies and new research methods advance scientific knowledge in high energy physics and a broad range of related fields, advancing the DOE's strategic goals for science.

The Accelerator Stewardship subprogram supports R&D efforts that are synergistic with the HEP mission but also impacts activities outside the traditional HEP boundaries. The activities of the Stewardship subprogram include: improving access to Office of Science (SC) accelerator R&D infrastructure for the private sector and other users; near-term translational R&D to adapt HEP accelerator technology for potential uses in medical, industrial, security, and defense applications; and long-term R&D for science and technology needed to build future generations of accelerators, with a focus on transformational opportunities.

HEP supports individual investigators and small-scale collaborations, as well as very large international collaborations, chosen for their scientific merit and potential for significant impact. More than 20 HEP-supported physicists have received the Nobel Prize in physics. Moreover, many of the advanced technologies, research tools, and analysis techniques originally developed for high energy physics have proved widely applicable to other scientific disciplines as well as for health services, national security, and the private sector.

Highlights of the FY 2019 Request

The P5 report identified the LHC upgrades, including the High-Luminosity Large Hadron Collider (HL-LHC) accelerator and A Toroidal LHC Apparatus (ATLAS) and Compact Muon Solenoid (CMS) Detector Upgrade Projects, as the highest priority in the near-term, and the Long Baseline Neutrino Facility and Deep Underground Neutrino Experiment (LBNF/DUNE) as the highest-priority large project in the P5 report's timeframe. To maintain the strong international partnership with CERN, the FY 2019 Request will increase support to these high-priority projects. The FY 2019 Request will support the planned funding profiles of LBNF/DUNE, HL-LHC Accelerator Upgrade Project, Muon to Electron Conversion Experiment (Mu2e), the Large Underground Xenon (LUX)-ZonEd Proportional scintillation in LIquid Noble gases (ZEPLIN) experiment (LZ), the Super Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Laboratory (SuperCDMS-SNOLAB), and the Dark Energy Spectroscopic Instrument (DESI). The Mu2e and LZ projects will receive final funding needed to complete all remaining project deliverables. The FY 2019 Request will support design and fabrication for the Facility for Advanced Accelerator Experimental Tests II (FACET-II) project, and preliminary design and prototyping for the planned Proton Improvement Plan II (PIP-II) project. The FY 2019 Request will include funding for two new Major Items of Equipment (MIEs), the HL-LHC ATLAS Detector Upgrade and the HL-LHC CMS Detector Upgrade projects. The FY 2019 Request will focus support for HEP research on the laboratory research programs that are critical to executing the P5 recommendations, and on world-leading R&D efforts that require long-term investments, including General Accelerator R&D (GARD), Detector R&D, Accelerator Stewardship, and QIS.

<u>Energy Frontier Experimental Physics</u>

The FY 2019 Request will support U.S. responsibilities and leadership roles on the LHC ATLAS and CMS experiments. The installation of the upgrades to the ATLAS and CMS detectors (MIE project funding for both completed in FY 2017) began in early FY 2018, and will continue during a two-year long technical stop of the LHC, which will start in 2019, to prepare the accelerator and detectors for a ramp up to the particle collision energy of 14 teraelectronvolts (TeV). In FY 2019, HEP will continue to invest in the future LHC program by contributing to the U.S. share of the HL-LHC Accelerator Upgrade Project and the HL-LHC ATLAS and CMS Detector Upgrade Projects to increase the particle collision rate by a factor of three times to explore new physics beyond the reach of the current LHC program.

Intensity Frontier Experimental Physics

The FY 2019 Request will support activities necessary to establish a U.S.-hosted, world-leading neutrino physics program, consisting of LBNF/DUNE, the related Short-Baseline Neutrino (SBN) program at Fermilab, and R&D efforts surrounding the prototypes for DUNE (protoDUNE) at CERN. The SBN program consists of a coordinated set of liquid-argon neutrino detector experiments, including the Short Baseline Neutrino Detector (SBND) and the Imaging Cosmic and Rare Underground Signals (ICARUS) detector, that will advance neutrino science and serve as an international R&D neutrino platform for LBNF/DUNE. The protoDUNE detectors at the CERN Neutrino Platform are testing full-scale elements of the DUNE detectors, using single-phase and dual-phase liquid-argon detector technologies. Both SBN and protoDUNE will begin taking data in FY 2019. The FY 2019 Request will support preliminary design and prototyping for the PIP-II project, which will upgrade the Fermilab linear accelerator to increase beam power and sustain high reliability of the Fermilab Accelerator Complex. PIP-II will provide the world's highest proton beam intensity of greater than 1.2 megawatts for LBNF/DUNE, which is necessary to enable the science program envisioned in the P5 report. The FY 2019 Request will support operations of the Fermilab Accelerator Complex at 75% of the optimal hours of service and two accelerator improvement projects (AIP) at Fermilab. The Neutrinos at the Main Injector (NuMI) Target System AIP will replace or refurbish the NuMI production target, replace its cooling systems, and upgrade critical infrastructure to make the overall system more robust and reliable for beam powers up to 1.0 megawatt. The Booster Intensity AIP will fabricate and install new components to the Booster accelerator to control the greater beam losses due to the increased proton beam intensity.

Cosmic Frontier Experimental Physics

The FY 2019 Request will support two complementary next-generation experiments that will advance our understanding of dark energy. The three billion pixel Large Synoptic Survey Telescope camera (LSSTcam), which will be installed on the LSST facility under construction by NSF in Chile, will scan half of the sky repeatedly with optical and near-infrared imaging sensors, building up a "cosmic cinematography" of the changing universe. DESI, on the Mayall Telescope in Arizona, will measure the distances of 30 million galaxies and quasars and create three-dimensional maps of the distribution of matter over two-thirds of the age of the universe. The LSSTcam and DESI projects will be in their fabrication phases in FY 2019. Commissioning and pre-operations activities for the overall LSST and DESI experiments will take place in FY 2019. The FY 2019 Request will support two second-generation direct-detection dark matter experiments, LZ and SuperCDMS-SNOLAB, which will carry out complementary searches for dark matter candidates over a broad range of masses. LZ will use a liquid xenon based detector located at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, and will receive final funding in FY 2019 to complete fabrication. SuperCDMS-SNOLAB, done in partnership with NSF, will use low-temperature solid-state detectors located at SNOLAB in Sudbury, Canada and will be in its fabrication phase in FY 2019. Pre-operations activities for the LZ and SuperCDMS-SNOLAB experiments will take place in FY 2019.

Theoretical and Computational Physics

The FY 2019 Request will support major theoretical research thrusts that focus on the P5 science drivers, intertwining the physics of the Higgs boson, neutrino masses, the dark universe, and exploring the unknown. Computational physics efforts will focus on advancing emerging computational science techniques, models, and technology necessary to meet the projected computing and data management needs of the HEP program. The FY 2019 Request will increase funding for QIS to accelerate discovery in particle physics while advancing the national program. HEP QIS efforts will focus on opportunities to address the P5 science drivers via foundational research including field theory and analog simulations, advanced technology including quantum controls and precision sensors, and computing approaches including optimization and machine learning.

Advanced Technology R&D

The FY 2019 Request will support world-leading Advanced Technology R&D that will enable transformative technology for the next-generation of accelerators and particle detectors. The FACET-II project at SLAC National Accelerator Laboratory (SLAC) will continue fabrication of the electron-beam driven plasma wakefield acceleration system. The Berkeley Laboratory Laser Accelerator (BELLA) at the Lawrence Berkeley National Laboratory (LBNL) will continue its world-leading program in laser-driven plasma wakefield accelerator research. Funding to initiate an AIP at LBNL will add a second beamline that can deliver an independently controlled laser pulse to a second laser-driven plasma wakefield acceleration structure, enabling tests of multistage particle acceleration. The HEP General Accelerator R&D (GARD) activity will continue the Traineeship Program for Accelerator Science and Technology, launched in FY 2017, to revitalize graduate level training and innovation in the physics of particle accelerators for the benefit of HEP and other SC programs that rely on these enabling technologies. The Detector R&D subprogram will be developing cutting-edge instrumentation to enable experimental research at the forefront of the field while training the next generation of detector experts.

Accelerator Stewardship

The FY 2019 Request will support R&D to develop the fundamental building blocks of new technological advances in accelerator technology, to empower the private sector to accelerate research discoveries from the laboratory to the marketplace, and to support the mission of other federal agencies. Funding to initiate an AIP at Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF) is requested to upgrade the Carbon Dioxide (CO_2) laser to a world-leading peak power of 20 Terawatts (TW).

Construction

The FY 2019 Request will include funding for the LBNF/DUNE project to continue the Critical Decision (CD)-3A approved scope for the far site civil construction for the excavation of the underground equipment caverns and connecting drifts (tunnels), and for the continued design work for the near site, cryogenic systems, and the DUNE detectors. The Muon to Electron Conversion Experiment (Mu2e) will complete the procurements and installation of the accelerator beam and detector equipment in FY 2019 according to its approved baseline funding profile.

High Energy Physics
Funding ($K)

	FY 2017 Enacted	FY 2018 Annualized CR[a]	FY 2019 Request	FY 2019 Request vs FY 2017 Enacted
Energy Frontier Experimental Physics				
Research	74,911	—	56,119	-18,792
Facility Operations and Experimental Support	52,420	—	44,309	-8,111
Projects	24,017	—	77,000	+52,983
SBIR/STTR	5,185	—	3,804	-1,381
Total, Energy Frontier Experimental Physics	**156,533**	**—**	**181,232**	**+24,699**
Intensity Frontier Experimental Physics				
Research	55,245	—	41,246	-13,999
Facility Operations and Experimental Support	153,066	—	125,916	-27,150
Projects	24,569	—	26,000	+1,431
SBIR/STTR	7,768	—	7,008	-760
Total, Intensity Frontier Experimental Physics	**240,648**	—	**200,170**	**-40,478**
Cosmic Frontier Experimental Physics				
Research	48,750	—	31,506	-17,244
Facility Operations and Experimental Support	12,335	—	11,320	-1,015
Projects	74,400	—	30,850	-43,550
SBIR/STTR	2,330	—	1,770	-560
Total, Cosmic Frontier Experimental Physics	**137,815**	—	**75,446**	**-62,369**
Theoretical and Computational Physics				
Research				
Theory	48,429	—	35,053	-13,376
Computational HEP	7,696	—	8,727	+1,031
Quantum Information Science	0	—	27,500	+27,500
Total, Research	56,125	—	71,280	+15,155
Projects	2,000	—	0	-2,000
SBIR/STTR	2,206	—	2,700	+494
Total, Theoretical and Computational Physics	**60,331**	—	**73,980**	**+13,649**

[a] A full-year 2018 appropriation for this account was not enacted at the time the budget was prepared; therefore, the budget assumes this account is operating under the Continuing Appropriations Act, 2018 (Division D of P.L. 115-56, as amended). The amounts included for 2018 reflect the annualized level provided by the continuing resolution. (These amounts are shown only at the Congressional control level and above; below that level, a dash (—) is shown).

	FY 2017 Enacted	FY 2018 Annualized CR[a]	FY 2019 Request	FY 2019 Request vs FY 2017 Enacted
Advanced Technology R&D				
Research				
HEP General Accelerator R&D	44,050	—	38,043	-6,007
HEP Directed Accelerator R&D	22,800	—	0	-22,800
Detector R&D	16,989	—	15,240	-1,749
Total, Research	83,839	—	53,283	-30,556
Facility Operations and Experimental Support	30,450	—	25,525	-4,925
Projects	3,500	—	2,000	-1,500
SBIR/STTR	4,293	—	2,947	-1,346
Total, Advanced Technology R&D	**122,082**	—	**83,755**	**-38,327**
Accelerator Stewardship				
Research	6,703	—	8,032	+1,329
Facility Operations and Experimental Support	6,891	—	3,950	-2,941
SBIR/STTR	497	—	435	-62
Total, Accelerator Stewardship	**14,091**	—	**12,417**	**-1,674**
Subtotal, High Energy Physics	**731,500**	**726,532**	**627,000**	**-104,500**
Construction				
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment	50,000	49,660	113,000	+63,000
11-SC-41, Muon to Electron Conversion Experiment	43,500	43,205	30,000	-13,500
Total, Construction	**93,500**	**92,865**	**143,000**	**+49,500**
Total, High Energy Physics	**825,000**	**819,397**	**770,000**	**-55,000**

SBIR/STTR Funding:
- FY 2017 Enacted: SBIR $19,532,000; and STTR: $2,747,000
- FY 2019 Request: SBIR $16,363,000; and STTR $2,301,000

High Energy Physics
Explanation of Major Changes ($K)

	FY 2019 Request vs FY 2017 Enacted
Energy Frontier Experimental Physics: The Request includes funding to support the new MIE starts for the HL-LHC ATLAS and HL-LHC CMS Detector Upgrade Projects, which will begin long-lead procurements, and an increase for the HL-LHC Accelerator Upgrade Project to begin full production of focusing magnets. This increase will be partially offset by the planned conclusion of the LHC ATLAS and CMS Detector Upgrade projects initiated in FY 2015. The Request prioritizes support to laboratory research activities critical to executing the P5 projects recommended to address Higgs boson science. The Request includes funding for commissioning of the LHC ATLAS and CMS Detector Upgrade projects.	+24,699
Intensity Frontier Experimental Physics: The Request prioritizes delivering particle beams and providing experimental operations at the Fermilab Accelerator Complex. Research support places higher priority on laboratory activities critical to executing the P5 projects recommended to address the neutrino mass and explore the unknown science drivers and carry out the early physics data analyses from operating experiments. The Request includes funding to work with international partners on the preliminary design and prototyping for the PIP-II project and to SURF operations that will support LBNF/DUNE construction.	-40,478
Cosmic Frontier Experimental Physics: The Request includes funding to complete the fabrication and installation of the LZ project, and continues the fabrication of the DESI and SuperCDMS-SNOLAB projects. The LSSTcam project funding concludes as planned. The FY 2019 Request prioritizes support to laboratory research activities critical to executing the P5 projects recommended to address the dark matter and dark energy science drivers. The Request includes funding for the installation, commissioning, and pre-operations activities for LSST, DESI, LZ, and SuperCDMS-SNOLAB.	-62,369
Theoretical and Computational Physics: The Request increases funding for Quantum Information Science (QIS) research, with a focus on quantum computing, algorithms, controls and sensors. The Request prioritizes support to theoretical research that addresses the neutrino mass science driver and to advanced computing research for HEP future needs. The Lattice Quantum Chromodynamics (LQCD) project received final funding in FY 2017.	+13,649
Advanced Technology R&D: The Request prioritizes support for world-leading, long-term R&D efforts at the national laboratories. The Request includes funding that focuses on accelerator, test beam and detector facilities that support the highest priority activities in the P5 report. The start of the LBNL BELLA Second Beamline accelerator improvement project (AIP) will offset the completion of the SLAC Sector 10 Injector Infrastructure AIP. The Muon Accelerator Program (MAP) completed its R&D goals in FY 2017, and the LHC Accelerator Research Program (LARP) anticipates completing its R&D goals before FY 2019.	-38,327
Accelerator Stewardship: The Request prioritizes support for long-term R&D for the science and technology needed to build future generations of accelerators with broad applicability and provides support to an AIP to upgrade the BNL ATF's Carbon Dioxide (CO_2) laser to a world-leading peak power of 20 Terawatt (TW).	-1,674
Construction: The Request increases funding to LBNF/DUNE in support of far site civil construction and excavation of the underground equipment caverns and connecting drifts. This increase will be partially offset by a planned decrease in funding to Mu2e for its final year of construction funding.	+49,500
Total, High Energy Physics	**-55,000**

Basic and Applied R&D Coordination
Accelerator Stewardship provides the fundamental building blocks of new technological advances in accelerator applications, including advanced proton and ion beams for the treatment of cancer, in coordination with the National Institutes of Health (NIH). HEP developed the Accelerator Stewardship subprogram based on input from accelerator R&D experts drawn from other federal agencies, universities, national laboratories, and the private sector to help identify specific research areas and infrastructure gaps where HEP investments would have sizable impacts beyond the SC research mission. This program is closely coordinated with the SC's Basic Energy Sciences (BES) and Nuclear Physics (NP) programs and partner agencies to ensure federal stakeholders have input in crafting funding opportunity announcements, reviewing applications, and evaluating the efficacy and impact of funded activities. Use-inspired accelerator R&D for medical applications has been closely coordinated with the NIH/National Cancer Institute (NCI); ultrafast laser technology R&D with the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA); and microwave and high power accelerator R&D coordinated with the DOD, the Department of Homeland Security's Domestic Nuclear Detection Office (DHS/DNDO), the NSF/Chemical, Bioengineering, Environmental and Transport (CBET) Systems Division, and the DOE's Office of Environmental Management (EM). Discussions with the National Nuclear Security Administration (NNSA) on mission needs and R&D coordination in laser technology, radioactive source replacement, and particle detector technologies are underway.

The Accelerator Stewardship subprogram conducts use-inspired basic R&D to provide the fundamental building blocks of new technological advances. Ensuring that the investments result in high-impact applications requires close coordination with other agencies who will carry on the later-stage development. The implementation strategy is to work with applied R&D agencies to jointly define priority research directions at Basic Research Needs Workshops, and then guide R&D and facility investments through joint participation of applied agency program managers in merit reviews and in the operations review of the Brookhaven National Laboratory Accelerator Test Facility. Where an eventual marketable use is envisioned, R&D collaborations are expected to involve a U.S. company to guide the early-stage R&D.

Specific funded examples include collaborative R&D on proton therapy delivery systems (joint with Varian Medical Systems), advanced proton sources for therapy (joint with ProNova Solutions), advanced detectors for cancer therapy (joint with Best Medical International) advanced microwave source development (joint with Communications Power Industries), and technical design studies for high power accelerators for wastewater treatment (joint with Metropolitan Water Reclamation District of Greater Chicago). Funded R&D awards have drawn an average of 20% of voluntary cost sharing over the first two years of the program, providing evidence of the potential impact.

Program Accomplishments
Record-breaking LHC performance continues, enabling new avenues to explore the Higgs boson and perform precision tests of the Standard Model (Energy Frontier). The LHC is the highest energy particle collider in the world and continues to break performance records and exceed its goals for producing particle collisions. The CMS experiment produced the first direct observation of the Higgs boson decaying to tau leptons, the heaviest known cousin of an electron. These first results are consistent with the prediction of the Standard Model of particle physics, but open a new window to exploring the universe through precision tests of the Higgs boson. The ATLAS experiment measured the mass of the W boson, a carrier particle of the weak nuclear force, to a precision of 2.4%, matching the precision of the best previous measurement. This new measurement enables important tests of the self-consistency of the Standard Model. The LHC aims to continue running at its record pace through 2018, before a two-year long technical stop to perform machine and detector upgrades, which will enable more detailed measurements of the Higgs boson and more sensitive searches for new physics.

COHERENT experiment uses the world's smallest neutrino detector to make the first observation of coherent scattering of low-energy neutrinos off nuclei (Intensity Frontier). In coherent scattering, a neutrino interacts with the entire atomic nucleus at once, not just one of the protons or neutrons within. The research performed at the Oak Ridge National Laboratory's (ORNL) Spallation Neutron Source (SNS) by a collaboration of 80 researchers from 19 institutions and 4 nations confirms the process originally predicted by theorists in 1974. Coherent scattering dominates neutrino dynamics during neutron star formation and supernovae explosions. Understanding coherent scattering will improve the scientific reach of future neutrino and dark matter experiments.

The Dark Energy Survey (DES) experiment produced its first precision measurements of dark energy (Cosmic Frontier). DES released the first dark energy results based on its imaging measurements of 26 million galaxies from the 570 million pixel Dark Energy camera on the Blanco telescope in Chile. The data was from the first year of the five-year wide-area survey, scheduled to end in 2018. The weak gravitational lensing effect, where gravity slightly distorts images of distant galaxies, was used to construct the largest-ever map of the distribution of ordinary and dark matter in the universe and its evolution over time. The results, within the 5% measurement uncertainty, are consistent with dark energy being an inherent property of the universe as opposed to a new kind of force. The full wide-area survey will cover approximately four times the area of the sky, include measurements of 300 million galaxies and thousands of supernovae, and enable precision cosmology results using a variety of methods to yield further insight into the dark universe.

First demonstration of laser-controlled injection in a beam-driven plasma wakefield accelerator at the Facility for Advanced Accelerator Experimental Tests (FACET) (Advanced Technology R&D). An experiment at FACET successfully used a laser pulse to generate an electron bunch within a plasma wakefield. FACET experiments previously demonstrated the high gradient and highly efficient wakefield acceleration of particles "surfing" on electromagnetic waves in plasma by using externally injected electron bunches. The demonstration of laser-controlled injection shows that unprecedented beam control and quality are feasible in plasma wakefield accelerators. This technology may drastically improve the performance of particle accelerators, with applications ranging from modern light sources to high energy colliders for future particle physics research.

First beam delivered to the Muon g-2 experiment at the Fermilab Muon Campus (Intensity Frontier). The Fermilab Muon Campus will host precision experiments, including the Muon-to-Electron Conversion (Mu2e) and Fermilab Muon g-2 experiments, which will search for new physics using beams of muons, heavy cousins of electrons. In May 2017, the Muon g-2 experiment received its first muon beam from the Fermilab Accelerator Complex, marking the start of three year campaign to measure an intrinsic property of the muon called the magnetic moment with unprecedented precision. The muons circulated in a 50-foot wide magnetic storage ring at Fermilab in Illinois. In the summer of 2013, the storage ring traveled a 3,200 mile route from Brookhaven National Laboratory in New York, where it was used for a previous Muon g-2 experiment in the 1990s.

Groundbreaking ceremony for the Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment (LBNF/DUNE) (Intensity Frontier). A new era in international particle physics research began on July 21, 2017, with a unique groundbreaking ceremony held a mile underground at the Sanford Underground Research Facility in South Dakota. Dignitaries, scientists, and engineers from around the world gathered to mark the start of initial far-site construction for the international science facility that will host massive experiments that may change our understanding of the universe. When complete, LBNF/DUNE will be the largest experiment ever built in the United States to study the properties of neutrinos, which may hold the key to understanding why matter and not antimatter dominates the universe today.

High Energy Physics
Energy Frontier Experimental Physics

Description

The Energy Frontier subprogram's focus is on the Large Hadron Collider (LHC). The LHC hosts two large multi-purpose particle detectors, ATLAS and CMS, which are partially supported by DOE and the NSF and used by large international collaborations of scientists. U.S. researchers account for approximately 20% and 25% of the ATLAS and CMS collaborations respectively, and play critical leadership roles in all aspects of each experiment. Data collected by ATLAS and CMS will be used to address at least three of the five science drivers identified by the P5 report:

- *Use the Higgs boson as a new tool for discovery*
  In the Standard Model of particle physics, the Higgs boson is responsible for generating the mass for all fundamental particles. Since the 2012 Nobel-winning discovery, experiments at the LHC continue to actively measure the Higgs's properties to establish its exact character and discover if there are additional effects that are the result of new physics beyond the Standard Model.
- *Explore the unknown: new particles, interactions, and physical principles*
  Researchers at the LHC probe for evidence of what lies beyond the Standard Model or significantly constrain postulated modifications to it, such as supersymmetry, mechanisms for black hole production, extra dimensions, and other exotic phenomena. The LHC detectors will be increasingly more sensitive to potential deviations from the Standard Model that may be exposed by the highest energy collisions in the world.
- *Identify the new physics of dark matter*
  If dark matter particles are light enough, they may be produced in LHC collisions and their general properties may be measured indirectly through the behavior of the accompanying normal matter. This indirect detection of dark matter is complementary to, and a powerful cross-check on, the ultra-sensitive direct detection experiments in the Cosmic Frontier and Intensity Frontier.

<u>Research</u>

The Energy Frontier experimental research activity consists of groups at U.S. academic and research institutions and physicists from national laboratories. These groups, as part of the ATLAS and CMS collaborations, typically have a broad portfolio of responsibilities and leadership roles in support of R&D, experimental design, fabrication, commissioning, operations, and maintenance, and they perform scientific simulations and physics data analyses. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. An external peer review of the Energy Frontier laboratory research groups was conducted in 2015; the next review will be in 2019. The findings from this review are being used to inform the funding decisions in subsequent years.

<u>Facility Operations and Experimental Support</u>

U.S. LHC Detector Operations funding supports the maintenance of U.S.-supplied detector systems for the ATLAS and CMS detectors at the LHC, and the U.S.-based computer infrastructure used by U.S. physicists to analyze LHC data, including Tier 1 computing centers at Fermilab and BNL. The Tier 1 centers provide around-the-clock support for the LHC Computing Grid; are responsible for storing a portion of raw and processed data; perform large-scale data reprocessing; and store the corresponding output.

<u>Projects</u>

During the next decade, CERN will undergo a major upgrade to the LHC machine to further increase the particle collision rate by a factor of three times to explore new physics beyond the reach of the current LHC program. Through the HL-LHC Accelerator Upgrade Project, HEP will contribute to this upgrade by constructing and delivering the next-generation of superconducting accelerator components in which U.S. scientists have critical expertise. After the upgrade, the HL-LHC beam will make the conditions in which the ATLAS and CMS detectors must operate very challenging. As a result, the HL-LHC ATLAS and HL-LHC CMS Detector Upgrades (new MIE starts) are critical investments to enable the experiments to operate for an additional decade and collect more data by a factor of ten.

Activities and Explanation of Changes

FY 2017 Enacted	FY 2019 Request	Explanation of Changes FY 2019 Request vs FY 2017 Enacted
Energy Frontier Experimental Physics $156,533,000	**$181,232,000**	**+$24,699,000**
Research $74,911,000	**$56,119,000**	**-$18,792,000**
Funding supported U.S. scientists leading high-profile analysis topics using the data collected by the ATLAS and CMS experiments at the LHC.	The FY 2019 Request will support U.S. leadership roles in all aspects of the ATLAS and CMS experiments.	Higher priority will be given to support laboratory research activities critical to executing the P5 projects recommended to address the Higgs boson science driver, and to carry out the final analyses on the data collected prior to the two-year long technical stop of the LHC, which will start in 2019.
Facility Operations and Experimental Support $52,420,000	**$44,309,000**	**-$8,111,000**
Funding supported ATLAS and CMS detector maintenance and operations including the U.S.-based computing infrastructure and resources used by U.S. scientists to analyze LHC data.	The FY 2019 Request will support ATLAS and CMS detector maintenance activities, including those related to commissioning of U.S.-built detector components during the two-year long technical stop of the LHC, which will start in 2019.	Focus of support will be on the commissioning following the installation of the LHC ATLAS and CMS Detector Upgrade projects initiated in FY 2015. Reduced support for compute nodes and data storage will be anticipated as a result of lower demand on the U.S.-based computing infrastructure during the two-year long technical stop of the LHC.
Projects $24,017,000	**$77,000,000**	**+$52,983,000**
Funding supported the fabrication and component installation for the LHC ATLAS Detector Upgrade and the LHC CMS Detector Upgrade projects. Funding supported the conceptual design activities for the HL-LHC Accelerator Upgrade Project and the HL-LHC ATLAS and HL-LHC CMS Detector Upgrade Projects.	The FY 2019 Request will support the procurement of solid-state detecting components for the HL-LHC ATLAS and HL-LHC CMS Detector Upgrade Projects (new MIE starts), and the production of focusing magnets for the HL-LHC Accelerator Upgrade Project.	Funding will support new MIE starts for the HL-LHC ATLAS and HL-LHC CMS Detector Upgrade Projects and the planned increase for the HL-LHC Accelerator Upgrade Project. The funding for the LHC ATLAS Detector Upgrade and the LHC CMS Detector Upgrade projects concluded as planned in FY 2017.
SBIR/STTR $5,185,000	**$3,804,000**	**-$1,381,000**
In FY 2017, SBIR/STTR funding was at 3.65% of non-capital funding.	In FY 2019, SBIR/STTR funding will be at 3.65% of non-capital funding.	A decrease in funding will represent mandated percentages for non-capital funding.

High Energy Physics
Intensity Frontier Experimental Physics

Description

The Intensity Frontier subprogram investigates some of the rarest processes in nature including unusual interactions of fundamental particles or subtle effects requiring large data sets to observe and measure. This HEP subprogram focuses on using high-power particle beams or other intense particle sources to make precision measurements of fundamental particle properties. These measurements in turn probe for new phenomena that cannot be directly observed at the Energy Frontier, either because they occur at much higher energies and their effects can only be seen indirectly, or because they are due to interactions that are too weak to be detected in high-background conditions at the LHC. Data collected from Intensity Frontier experiments during this period will be used to address at least three of the five science drivers identified by the P5 report:

- *Pursue the physics associated with neutrino mass*
  Of all known particles, neutrinos are perhaps the most enigmatic and certainly the most elusive. HEP researchers working at U.S. facilities discovered all of the three known varieties of neutrinos. HEP supports research into fundamental neutrino properties that may reveal important clues about the unification of forces and the very early history of the universe. The Intensity Frontier-supported portfolio of neutrino experiments will advance neutrino physics while serving as an international platform for the R&D activities necessary to establish the U.S.-hosted international LBNF/DUNE.
- *Explore the unknown, new particles, interactions, and physical principles*
  A number of observed phenomena are not described by the Standard Model, including the imbalance of matter and antimatter in the universe today. Precision measurements of the properties of known particles can reveal information about what new particles and forces could explain these discrepancies and whether the known forces unify at energies beyond the reach of the LHC.
- *Identify the new physics of dark matter*
  The lack of experimental evidence from current generation dark matter detectors has led to proposed theoretical models with new particles and forces that rarely interact with normal matter. These theoretical particles and forces are effectively invisible to conventional experiments, but may be connected to the cosmic dark matter. Experiments use intense accelerator beams at national laboratories outfitted with highly efficient high-rate detectors to explore these theoretical models.

Research

The Intensity Frontier experimental research activity consists of groups at U.S. academic and research institutions and national laboratories that perform experiments. These groups, as part of scientific collaborations, typically have a broad portfolio of responsibilities and leadership roles in support of R&D, experimental design, fabrication, commissioning, operations, and maintenance, as well as perform scientific simulations and physics data analyses on the experiments in the subprogram. DOE selects research efforts with the highest scientific merit and potential impact based on a competitive peer-review process. An external peer review of the Intensity Frontier laboratory research groups is planned for 2018. The findings from this review will inform the funding decisions in subsequent years.

The largest component of the Intensity Frontier subprogram is the support for research in accelerator-based neutrino physics centered at Fermilab with multiple experiments running concurrently in two separate neutrino beams with different beam energies. The flagship NuMI Off-Axis ν_e Appearance (NOvA) experiment uses the Neutrinos at the Main Injector (NuMI) beam, and the Booster Neutrino Beam (BNB) are used to study different aspects of neutrino physics and muon physics. The SBN program, which includes the Imaging Cosmic and Rare Underground Signals (ICARUS) and Short Baseline Neutrino Detector (SBND) experiments, use the BNB to definitively address hints of additional neutrinos types beyond the three currently described in the Standard Model. The protoDUNE detectors are testing single-phase and dual-phase liquid-argon detector technologies to inform the design efforts for DUNE. LBNF/DUNE will be the centerpiece of a U.S.-hosted world-leading neutrino program, using the world's most intense neutrino beam and large, sensitive underground detectors to make transformative discoveries.

The Intensity Frontier muon program at Fermilab studies rare processes in muons to detect physics beyond the reach of the LHC. The Muon g-2 experiment, with four times better precision, is following up on hints of new physics from an earlier experiment, while the Mu2e experiment searches for extremely rare muon decays that (if detected) will be clear evidence of new physics. The Intensity Frontier subprogram supports U.S. physicists to participate in select experiments at foreign facilities, including neutrino experiments in China and Japan. There is a U.S. contingent studying heavy particles containing b-quarks using the Belle II experiment at the High Energy Accelerator Research Organization (KEK) in Japan.

Facility Operations and Experimental Support

There are several distinct facility operations and experimental support efforts in the Intensity Frontier subprogram. The largest is the Fermilab Accelerator Complex User Facility. This activity includes the operations of all accelerators and beamlines at Fermilab and the operation of the detectors that use those accelerators as well as computing support needed by both the accelerators and detectors. General Plant Project (GPP) and Accelerator Improvement Project (AIP) funding supports improvements to Fermilab facilities.

Fermilab contracts with the South Dakota Science and Technology Authority (SDSTA), an agency of the State of South Dakota, for services at the Sanford Underground Research Facility (SURF) to support DOE experiments being conducted there. The Nuclear Physics-supported Majorana Demonstrator is currently operating and the HEP-supported LZ experiment is being installed at SURF, which will be the home of the DUNE far detectors built by the LBNF/DUNE project.

Projects

In support of LBNF/DUNE, a lease with SDSTA provides the framework for DOE and Fermilab to construct federally funded buildings and facilities on non-federal land, and to establish a long-term (multi-decade) arrangement for DOE and Fermilab to use SDSTA space to host the DUNE neutrino detector. Other Project Costs (OPC) funding has been identified for SURF plant support costs provided by SDSTA.

The planned PIP-II will provide a 1.2 megawatt beam to LBNF/DUNE, which is higher than the 0.7 megawatt beam used by NOvA. The front-end is the oldest part of the Fermilab Accelerator Complex and needs to be replaced to improve reliability and to produce higher intensity muon and neutrino beams. Fermilab is developing a conceptual design and establishing partnerships with institutions in India, Italy, and the United Kingdom to contribute to the project.

Activities and Explanation of Changes

FY 2017 Enacted	FY 2019 Request	Explanation of Changes FY 2019 Request vs FY 2017 Enacted
Intensity Frontier Experimental Physics $240,648,000	**$200,170,000**	**-$40,478,000**
Research $55,245,000	**$41,246,000**	**-$13,999,000**
Funding supported research efforts to analyze data from operating long- and short-baseline neutrino experiments, beam-based dark matter experiments, precision measurement experiments that explore the unknown, and for design and physics optimization for projects in their fabrication phase.	The FY 2019 Request will support U.S. leadership on all aspects of the neutrino and muon experiments including NOvA, ICARUS and Muon g-2, and the future projects including LBNF/DUNE and Mu2e. The first physics data results from Belle II will be anticipated.	Higher priority will be given to support laboratory research activities critical to executing the P5 projects recommended to address the neutrino mass and explore the unknown science drivers, and to carry out the early physics data analyses from Muon g-2, Belle II, SBN program and protoDUNE.
Facility Operations and Experimental Support $153,066,000	**$125,916,000**	**-$27,150,000**
Funding supported the operation of the Fermilab Accelerator Complex and the neutrino and muon experiments. The refurbishment of the Linac and BNB continued. Construction of an addition to the Industrial Center Building (ICB) began as a new GPP. SURF operations supported the ongoing Majorana demonstrator activities and preparations for the LZ experiment and LBNF/DUNE construction.	The FY 2019 Request will support the operation of the Fermilab Accelerator Complex and the neutrino and muon experiments, while the running time of the Main Injector and Booster accelerators will be shortened to 75% of optimal. SURF operations will continue to support the LBNF/DUNE construction and the commissioning of the LZ experiment. The Fermilab NuMI Target System and Booster Intensity AIPs will begin.	Support will prioritize delivering the particle beams and providing experimental operations for ongoing experiments, including NOvA, the SBN program, and Muon g-2, in a manner that will optimize addressing the P5 science drivers.
Projects $24,569,000	**$26,000,000**	**+$1,431,000**
Funding supported the fabrication of the Muon g-2 beamline and detectors, OPC to continue the conceptual design for the PIP-II project, and subsystems integration and infrastructure for the SBN program.	The FY 2019 Request will support OPC for the preliminary design and prototyping of the most technologically advanced accelerator components for the PIP-II project, and the OPC for plant support costs at SURF during LBNF/DUNE construction.	Focus of support will be on working with international partners on preliminary design and prototyping for the PIP-II project. Funding for Muon g-2 project concluded as planned. OPC will begin for LBNF/DUNE with the ramp-up of CD-3A construction.
SBIR/STTR $7,768,000	**$7,008,000**	**-$760,000**
In FY 2017, SBIR/STTR funding was at 3.65% of non-capital funding.	In FY 2019, SBIR/STTR funding will be at 3.65% of non-capital funding.	A decrease in funding will represent mandated percentages for non-capital funding.

Description

The Cosmic Frontier subprogram uses measurements of naturally occurring cosmic particles and observations of the universe to probe fundamental physics questions and offer new insight about the nature of dark matter, dark energy, and inflation in the early universe, constraints on neutrinos and other phenomena. The activities in this subprogram use diverse tools and technologies, from ground-based telescopes and space-based missions to large detectors deep underground to address four of the five science drivers identified in the P5 report:

- *Identify the new physics of dark matter*
  Overwhelming evidence through the years, starting with measurements of motions within galaxies first made in the 1930s, show that dark matter accounts for five times as much matter in the universe as ordinary matter. Direct-detection experiments provide the primary method to search for cosmic dark matter particles' rare interactions with ordinary matter, while indirect-detection experiments search for the products of dark matter annihilation in the core of galaxies. A staged series of direct-detection experiments search for the leading theoretical candidate particles using multiple technologies to cover a wide range in mass with increasing sensitivity. Accelerator-based dark matter searches performed in the Intensity Frontier and the Energy Frontier subprograms are complementary to these direct-detection experiments.
- *Understand cosmic acceleration: dark energy and inflation*
  Since its 1999 discovery and subsequent 2011 Nobel Prize in Physics, the nature of dark energy, which drives the accelerating expansion of the universe, continues to be one of the most perplexing questions in science. Together, dark energy and dark matter comprise 95% of the matter and energy in the universe, leaving approximately 5% ordinary matter, from which all the stars and galaxies, and we, are made. Steady progress continues in a staged set of dark energy experiments, using complementary fast sky-scanning surveys and deep, high-accuracy surveys, which provide ever-increasing precision. Experiments studying the oldest observed light in the universe, the cosmic microwave background (CMB), are increasing their sensitivity to target the era of cosmic inflation, the rapid expansion in the early universe shortly after the Big Bang.
- *Pursue the physics associated with neutrino mass*
  Remarkably, the study of the largest physical structures in the Universe can reveal the properties of particles with the smallest known cross-section, the neutrinos. Experiments studying dark energy and the CMB will put constraints on the number of neutrino species and their masses. The properties of neutrinos affected the evolution of matter distribution in the universe, leading to changes in the CMB observables when measured in different directions. These measurements are complementary to, and a powerful cross check of, the ultra-sensitive measurements made in the Intensity Frontier.
- *Explore the unknown: new particles, interactions, and physical principles*
  High-energy cosmic rays and gamma rays probe energy scales well beyond what can be produced with man-made particle accelerators, albeit not in a controlled experimental setting. Searches for new phenomena and indirect signals of dark matter in these surveys may yield surprising discoveries about the fundamental nature of the universe.

<u>Research</u>

The Cosmic Frontier experimental research activity consists of groups at U.S. academic and research institutions and national laboratories who perform experiments using instruments on the surface, deep underground, and in space. These groups, as part of scientific collaborations, typically have a broad portfolio of responsibilities and leadership roles in support of R&D, experimental design, fabrication, commissioning, operations, and maintenance, as well as perform scientific simulations and physics data analyses on the experiments in the subprogram. DOE selects research efforts with the highest scientific merit and potential impact based on a competitive peer-review process. An external peer review of the Cosmic Frontier laboratory research groups was conducted in 2016; the next review will be in 2020. The findings from this review are being used to inform the funding decisions in subsequent years.

<u>Facility Operations and Experimental Support</u>

This activity support the DOE share of personnel, data processing, and other expenses necessary for the successful pre-operations planning activities and maintenance, operations, and data production during the operating phase of Cosmic Frontier experiments. These experiments are typically not sited at national laboratories. They are located at ground-based telescopes and observatories, in space, or deep underground. Support is provided for the experiments currently operating as well as for planning and pre-operations activities for the next generation experiments in the design or fabrication phase. HEP conducted a peer review of Cosmic Frontier operations in early FY 2015; the next review is planned for FY 2019. In the interim, HEP has held subsequent status reviews and operations planning reviews. HEP uses the findings from the reviews to monitor the experiments and inform decisions concerning the level of operations support needed in subsequent years.

Projects

P5 recommended a robust suite of next-generation dark energy and dark matter projects, with a potential CMB project starting later in the ten-year plan. Two experiments will use different survey types and methods to measure the effect of dark energy on the expansion of the universe, which allows differentiation between models of dark energy. The LSSTcam that will be installed on the LSST facility will scan half of the sky repeatedly with optical and near-infrared imaging sensors, building up a “cosmic cinematography” of the changing universe, while DESI will study 30 million galaxies and quasars with spectroscopy over two-thirds of the age of the universe. Two experiments will use different technologies to search for dark matter: LZ will use a liquid xenon detector and SuperCDMS-SNOLAB will use low-temperature solid-state detectors. LZ is better at detecting heavier dark matter particles while SuperCDMS-SNOLAB will be sensitive to lighter dark mass particles, so the two combine to provide the largest search currently feasible.

Activities and Explanation of Changes

FY 2017 Enacted	FY 2019 Request	Explanation of Changes FY 2019 Request vs FY 2017 Enacted
Cosmic Frontier Experimental Physics $137,815,000	**$75,446,000**	**-$62,369,000**
Research $48,750,000	**$31,506,000**	**-$17,244,000**
Funding supported research efforts to analyze current dark matter and dark energy experiments and for design and physics optimization for projects in their fabrication phase.	The FY 2019 Request will support world-leading research efforts in support of design and optimization on dark matter and dark energy experiments in their fabrication and commissioning phases, as well as on planning for future experiments, including CMB-S4.	Higher priority will be given to support laboratory research activities critical to executing the P5 projects recommended to address the dark matter and dark energy science drivers, and to carry out the final data analyses on Cosmic Frontier experiments completing in FY 2019.
Facility Operations and Experimental Support $12,335,000	**$11,320,000**	**-$1,015,000**
Funding supported the start of the early operations activities necessary for projects near completion, such as LSSTcam, and the operations of on-going experiments in the physics data-taking phase.	The FY 2019 Request will support the start of installation and commissioning activities for the LSSTcam, as well as early planning for the LSST facility and science operations. Planning, commissioning, and pre-operations activities will begin for DESI, LZ, and SuperCDMS-SNOLAB. Support for the currently operating experiments will continue.	Focus of support will be on the installation, commissioning and pre-operations activities for LSSTcam, DESI, LZ, and SuperCDMS-SNOLAB as these projects will begin the transition to experimental operations.
Projects $74,400,000	**$30,850,000**	**-$43,550,000**
Funding supported continued fabrication for the LSSTcam, LZ and DESI projects, and design work towards SuperCDMS-SNOLAB project baseline.	The FY 2019 Request will support the completion of fabrication and installation of the LZ dark matter project, and will support the fabrication of the DESI dark energy project and the SuperCDMS-SNOLAB dark matter project.	Priority will be given to support the fabrication and installation of the DESI, LZ, and SuperCDMS-SNOLAB projects. The LSSTcam project funding will conclude as planned.
SBIR/STTR $2,330,000	**$1,770,000**	**-$560,000**
In FY 2017, SBIR/STTR funding was at 3.65% of non-capital funding.	In FY 2019, SBIR/STTR funding is at 3.65% of non-capital funding.	A decrease in funding will represent mandated percentages for non-capital funding.

Theoretical and Computational Physics

Description

The Theoretical and Computational Physics subprogram provides the mathematical, phenomenological, and computational framework to understand and extend our knowledge of the dynamics of particles and fields, and the nature of space and time. This research is essential for proper interpretation and understanding of the experimental research activities described in other HEP subprograms. Theory and computation cut across all five P5 science drivers and the Energy, Intensity, and Cosmic Frontier Experimental Physics subprograms.

Theory

The HEP theory activity supports world-leading research groups at U.S. academic and research institutions and national laboratories. Both university and laboratory research groups play important roles in addressing the leading research areas discussed above. Laboratory groups are typically more focused on data-driven theoretical investigations and precise calculations of experimentally observable quantities. University groups usually focus on building models of physics beyond the Standard Model and studying their phenomenology as well as on formal and mathematical theory. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. An external peer review of the Theory laboratory research groups is planned for 2018. The findings from this review will inform the funding decisions in subsequent years.

Computational HEP

Computation is necessary at all stages of HEP experiments—from planning and constructing accelerators and detectors, to theoretical modeling, to supporting computationally intensive experimental research and large-scale data analysis. Computational HEP priorities are to advance computing research for HEP future needs across the program, including exploiting latest architectures. HEP partners with the Advanced Scientific Computing Research (ASCR), including via the Scientific Discovery through Advanced Computing (SciDAC) program, to optimize the HEP computing ecosystem for the near and long term future.

In addition to supporting the science and technology thrusts, Computational HEP fosters advanced simulations and computational science that extends the boundaries of scientific discovery to regions not directly accessible by experiments, observations, or traditional theory. Computational HEP activities have fostered HEP connections with the national effort on Quantum Information Science (QIS) and sponsored reports and pilot projects in support of the P5 science drivers and to advance discovery.

Quantum Information Science

The HEP QIS efforts will focus on foundational research on techniques and algorithms, quantum computing for HEP experiments and modeling, development and use of specialized quantum controls, and precision sensors that may yield information on fundamental physics beyond the Standard Model. This research area is part of an SC initiative that will be conducted in coordination with SC programs, other federal agencies, and the private sector where relevant.

Projects

The Projects activity funds acquisition of dedicated hardware for the Lattice Quantum Chromodynamics (LQCD) computing effort. This activity received final funding in FY 2017.

Activities and Explanation of Changes

FY 2017 Enacted	FY 2019 Request	Explanation of Changes FY 2019 Request vs FY 2017 Enacted
Theoretical and Computational Physics $60,331,000	**$73,980,000**	**+$13,649,000**
Theory $48,429,000	**$35,053,000**	**-$13,376,000**
Funding supported the theoretical research program at universities and national laboratories for the interpretation of experimental results, the development of new ideas for future projects, and the advancement of the theoretical understanding of nature.	The FY 2019 Request will support world-leading theoretical research program at universities and national laboratories.	Higher priority will be given to research that addresses the neutrino mass science driver.
Computational HEP $7,696,000	**$8,727,000**	**+$1,031,000**
Funding supported the computational science efforts focused at the national laboratories and the HEP contributions to the SciDAC 4 projects which were competed in FY 2017.	The FY 2019 Request will support transformative computational science and SciDAC 4 activities.	Higher priority will be given to advance computing research for HEP future needs, and working with ASCR to optimize the high performance computing for the near and long term future.
Quantum Information Science $0	**$27,500,000**	**+$27,500,000**
N/A	The FY 2019 Request will support new foundational QIS research and supporting technology. HEP will employ the latest developments in QIS from the private sector, contribute to the national effort, and promote American competiveness.	Focus of support will be on QIS research techniques and algorithms, quantum computing for HEP experiments and modeling, development and use of specialized quantum controls and precision sensors.
Projects $2,000,000	**$0**	**-$2,000,000**
Funding was provided for the acquisition of new LQCD hardware.	No funding will be requested for this activity.	LQCD received final funding in FY 2017.
SBIR/STTR $2,206,000	**$2,700,000**	**+$494,000**
In FY 2017, SBIR/STTR funding was at 3.65% of non-capital funding.	In FY 2019, SBIR/STTR funding will be at 3.65% of non-capital funding.	An increase in funding will represent mandated percentages for non-capital funding.

High Energy Physics
Advanced Technology R&D

Description

The Advanced Technology Research and Development (R&D) subprogram fosters cutting-edge research in the physics of particle beams, accelerator R&D, and particle detection—all of which are necessary for continued progress in high energy physics. Advanced Technology R&D cuts across all five P5 science drivers and the Energy, Intensity, and Cosmic Frontier Experimental subprograms. Long-term multi-purpose accelerator research, applicable to fields beyond HEP, is carried out under the Accelerator Stewardship subprogram.

HEP General Accelerator R&D

HEP General Accelerator R&D (GARD) focuses on understanding the science underlying the technologies used in particle accelerators and storage rings, as well as the fundamental physics of charged particle beams. Long-term research goals include developing technologies to enable breakthroughs in particle accelerator size, cost, beam intensity, and control. The GARD program consists of groups at U.S. academic and research institutions and national laboratories performing research activity categorized into five thrust areas: accelerator and beam physics; advanced acceleration concepts; particle sources and targetry; radio-frequency acceleration technology; and superconducting magnet and materials. GARD prioritizes research topics based on input from the April 2015 HEPAP Accelerator R&D subpanel report[a]. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. An external peer review of the GARD laboratory research groups is planned for 2018. The findings from this review will inform the funding decisions in subsequent years.

GARD supports the Traineeship Program for Accelerator Science and Technology, launched in FY 2017 to revitalize education, training, and innovation in the physics of particle accelerators for the benefit of HEP and other SC programs that rely on these enabling technologies. A component of this program allows graduate students to participate in mentored accelerator research and technology development and enable leveraging the capabilities and assets of DOE laboratories. HEP holds a competition for traineeship awards to increase workforce development in areas of critical need. These traineeships leverage existing GARD research programs to develop new curricula and course materials in areas of workforce needs. The Traineeship Program is aimed at a university and national laboratory consortium to provide the academic training and research experience needed to meet DOE's anticipated workforce needs.

HEP Directed Accelerator R&D

HEP Directed Accelerator R&D supports strategic investments in innovative technologies for possible future HEP accelerator projects, with proof-of-principle demonstrations, prototype component development, and advancing technical readiness. The Muon Accelerator Program (MAP) completed its R&D goals in FY 2017 by delivering and then commissioning components for the Muon Ionization Cooling Experiment at Rutherford Appleton Laboratory in the United Kingdom. The LHC Accelerator Research Program (LARP) is anticipated to complete its R&D goals to produce prototypes for U.S. deliverables to the HL-LHC Accelerator Upgrade Project at CERN before FY 2019.

Detector R&D

Detector R&D addresses the need for continuing development of the next generation instrumentation and particle detectors to keep scientific leadership in a worldwide experimental program that is broadening into new research areas. To meet this challenge, HEP aims to foster a program appropriately balanced between evolutionary, near-term, low-risk detector R&D and revolutionary, long-term, high-risk detector R&D, while training the next generation of experts. The Detector R&D subprogram consists of groups at U.S. academic and research institutions and national laboratories performing research into the fundamental physics underlying the interactions of particles and radiation in detector materials as well as the development of technologies that turn these insights into working detectors. DOE selects research efforts with the highest scientific impact and potential based on a competitive peer-review process. An external peer review of the Detector R&D laboratory research groups was conducted in 2016; the next review will be in 2020. The findings from this review are being used to inform the funding decisions in subsequent years.

[a] http://science.energy.gov/~/media/hep/hepap/pdf/Reports/Accelerator_RD_Subpanel_Report.pdf

Facility Operations and Experimental Support

This activity provides funding for GARD laboratory experimental and test facilities, including BELLA, the laser-driven plasma wakefield acceleration facility at LBNL, and the facility for studying intense beam dynamics, the superconducting radio-frequency accelerator facilities, and the magnet facilities at Fermilab. This activity funds detector test beams at SLAC National Accelerator Laboratory (SLAC) and Fermilab, and detector test and fabrication facilities like the Microsystems Laboratory at LBNL and the Silicon Detector Facility at Fermilab. Accelerator Improvement Project (AIP) funding supports improvements to GARD facilities.

Projects

The Advanced Technology R&D subprogram supports the development of new tools for particle physics through the development of more advanced accelerators and detectors. Plasma wakefield accelerators may have a transformative impact on the size, capabilities, and cost of future machines. FACET-II will support the continuation of the plasma wakefield acceleration research started at FACET which was displaced by the construction of Linac Coherent Light Source II (LCLS-II). FACET-II fabrication and installation will occur at SLAC during the LCLS shutdown in FY 2019 in preparation for LCLS-II.

Activities and Explanation of Changes

FY 2017 Enacted	FY 2019 Request	Explanation of Changes FY 2019 Request vs FY 2017 Enacted
Advanced Technology R&D $122,082,000	**$83,755,000**	**-$38,327,000**
HEP General Accelerator R&D $44,050,000	**$38,043,000**	**-$6,007,000**
Funding supported research activities following the roadmap developed with the Accelerator R&D community, with focus in the areas of advanced accelerator concepts and superconducting magnets. The Traineeship Program for Accelerator Science and Technology was started.	The FY 2019 Request will support world-leading research activities in the areas of accelerator and beam physics, advanced acceleration concepts, particle sources and targetry, radio-frequency acceleration technology and superconducting magnet and materials. The Traineeship Program for Accelerator Science and Technology will be supported.	High priority will be given to world-leading efforts supported at national laboratories, and to research programs recommended by the HEPAP Accelerator Subpanel.
HEP Directed Accelerator R&D $22,800,000	**$0**	**-$22,800,000**
Funding supported LARP to continue the R&D needed to produce prototypes for U.S. deliverables to the HL-LHC Accelerator Upgrade Project at CERN. MAP delivered the final components in FY 2017.	No funding will be provided as LARP anticipates completing its goals before FY 2019, and MAP completed its goals in FY 2017.	The LARP and MAP goals will have been met.
Detector R&D $16,989,000	**$15,240,000**	**-$1,749,000**
Funding supported research activities at universities and national laboratories, with increased emphasis on long-term, high-risk, and high potential impact Detector R&D efforts and strengthening of the university efforts.	The FY 2019 Request will support world-leading Detector R&D activities at universities and national laboratories, with increased emphasis on long-term, high-risk, and high potential impact R&D efforts.	Near-term Detector R&D activities will be ramped down.
Facility Operations and Experimental Support $30,450,000	**$25,525,000**	**-$4,925,000**
Funding supported operation of accelerator, test beam and detector facilities at Fermilab, LBNL and SLAC. The SLAC Sector 10 Injector Infrastructure AIP began.	The FY 2019 Request will support the operation of accelerator, test beam and detector facilities at Fermilab, LBNL and SLAC. The LBNL BELLA Second Beamline AIP will begin.	Funding support will be focused on the accelerator, test beam, and detector facilities at Fermilab. Funding for LBNL and SLAC will support the highest priority research and fabrication activities informed by the P5 report. The LBNL BELLA Second Beamline AIP will begin, offset by the completion of the SLAC Sector 10 Injector Infrastructure AIP.

FY 2017 Enacted	FY 2019 Request	Explanation of Changes FY 2019 Request vs FY 2017 Enacted
Projects $3,500,000	**$2,000,000**	**-$1,500,000**
Funding supported the start of fabrication for FACET-II.	The FY 2019 Request will support continued fabrication for FACET-II.	Focus of support will be on the critical FACET-II infrastructure that needs to be installed during the shutdown of the linac for the LCLS-II installation.
SBIR/STTR $4,293,000	**$2,947,000**	**-$1,346,000**
In FY 2017, SBIR/STTR funding was at 3.65% of non-capital funding.	In FY 2019, SBIR/STTR funding will be at 3.65% of non-capital funding.	A decrease in funding will represent mandated percentages for non-capital funding.

High Energy Physics
Accelerator Stewardship

Description

The Accelerator Stewardship subprogram has three principal activities: facilitating access to unique state-of-the-art SC accelerator R&D infrastructure for the private sector and other users; supporting innovative early-stage applied research to adapt accelerator technology for medical, industrial, security, and defense applications; and driving a limited number of specific accelerator applications towards practical, testable prototypes in a five to seven year timeframe. HEP manages this program as a coordinated interagency initiative, consulting with other SC programs (principally NP and BES), other DOE program offices (principally EM and NNSA), and other federal stakeholders[a] of accelerator technology, most notably NIH, DOD, NSF, and DHS.

Accelerator Stewardship pursues targeted R&D to develop new uses of accelerator technology with broad applicability. Initial workshops and a request for information identified target application areas with broad impact in accelerator technologies for ion beam therapy of cancer and laser technologies for accelerators. Ongoing interagency consultation guides R&D investments, ensuring agency priorities are addressed and exploiting synergies where possible. As the program evolves, it will identify new cross-cutting areas of research based on input from the federal stakeholders, R&D performers, and the U.S. private sector.

<u>Research</u>

Accelerator Stewardship research is conducted at national laboratories, universities, and in the private sector. The stewardship program supports both near-term translational R&D and long-term basic accelerator R&D. The needs for applications chosen for this category have been specifically identified by federal stakeholders and developed further by technical workshops. Near-term R&D funding opportunities are specifically structured to foster strong partnerships with the private sector to improve health outcomes while lowering cost, develop technologies that can destroy pollutants and pathogens, detect contraband and radioactive material, and support new tools of science. Long-term R&D funding is targeted at scientific innovations enabling breakthroughs in particle accelerator size, cost, beam intensity, and control.

<u>Facility Operations and Experimental Support</u>

The Accelerator Stewardship subprogram supports the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF), which is an SC User Facility providing a unique combination of high quality electron and infrared laser beams in a well-controlled user-friendly setting. Beam time at the BNL ATF is awarded based on merit-based peer review process. The facility remains at the cutting edge of science and works to increase its cost efficiency through an ongoing program of facility R&D. Accelerator Improvement Project (AIP) funding supports improvements to Accelerator Stewardship facilities.

[a] Partner agencies for the Accelerator Stewardship program currently are: the National Institutes of Health's National Cancer Institute; the Department of Defense's Office of Naval Research and Air Force Office of Scientific Research; the NSF's Physics Division and Chemical, Bioengineering, Environmental and Transport Systems Division; Department of Homeland Security's Domestic Nuclear Detection Office.

High Energy Physics
Accelerator Stewardship

Activities and Explanation of Changes

FY 2017 Enacted	FY 2019 Request	Explanation of Changes FY 2019 Request vs FY 2017 Enacted
Accelerator Stewardship $14,091,000	**$12,417,000**	**-$1,674,000**
Research $6,703,000	**$8,032,000**	**+$1,329,000**
Funding supported a robust program of early-stage translational R&D at laboratories, universities, and industry for technology R&D areas such as laser, ion-beam therapy, and accelerator technology.	The FY 2019 Request will support new research activities at laboratories, universities, and in the private sector for technology R&D areas such as accelerator technology for industrial and security uses, laser, and ion-beam therapy.	Priority will be given to long-term R&D for the science and technology needed to build future generations of accelerators.
Facility Operations and Experimental Support $6,891,000	**$3,950,000**	**-$2,941,000**
Funding supported the BNL ATF operations. The ATF II Upgrade AIP was completed.	The FY 2019 Request will support the BNL ATF operations. The 20TW CO2 Laser Upgrade AIP will begin.	The ATF II Upgrade AIP, completed under budget, will be partially offset by the start of the 20TW CO2 Laser Upgrade AIP.
SBIR/STTR $497,000	**$435,000**	**-$62,000**
In FY 2017, SBIR/STTR funding was at 3.65% of non-capital funding.	In FY 2019, SBIR/STTR funding will be at 3.65% of non-capital funding.	A decrease in funding will represent mandated percentages for non-capital funding.

High Energy Physics
Construction

Description

This subprogram supports all line-item construction for the entire HEP program. All Total Estimated Costs (TEC) are funded in this subprogram, including both engineering design and construction.

Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE)

The LBNF/DUNE construction project is a federal, state, private, and international partnership developing and implementing the technologies of particle accelerators and detectors to enable world-leading research into the fundamental physics of neutrinos, which are the most ubiquitous particles in the universe while at the same time among the most mysterious. Neutrinos are intimately involved in nuclear decay processes and high energy nuclear reactions. LBNF/DUNE will study the transformations of muon neutrinos that occur as they travel to a large detector in South Dakota, 800 miles away from Fermilab, where they are produced in a high-energy beam. The experiment will analyze the rare, flavor-changing transformations of neutrinos in flight, from one lepton flavor to another, which are expected to help explain the fundamental physics of neutrinos and the imbalance of matter and antimatter in the universe today.

The LBNF/DUNE is being managed as a single project that encompasses the construction of a particle beam at Fermilab and the infrastructure for DUNE detectors at SURF. Fermilab, as host, will oversee all LBNF/DUNE construction and is responsible for design, construction, and operation of the LBNF beamline; design, construction, and operation of the conventional facilities and experiment infrastructure on the Fermilab site required for the near detector; and design, construction, and operation of the conventional facilities and experiment infrastructure at SURF, including the cryostats and cryogenics systems, required for the far detector. DUNE is an international collaboration that has formed to carry out the neutrino experiment enabled by the LBNF facility. The DUNE collaboration will be responsible for: the definition of the scientific goals; the design, construction, commissioning, and operation of the near detector at Fermilab and the far detectors at SURF; and the scientific research program conducted with the DUNE detectors. The DUNE collaboration currently consists of about 1,000 scientists and engineers from over 160 institutes in over 30 countries. Each of the collaborating institutions is responsible for delivering in-kind detector components that they have proven to have the expertise to build and install. Presently, the DOE contribution to the detectors will be a minority portion of the scope.

The near-term critical path item for LBNF/DUNE is excavation of the equipment caverns. Installation of the cryogenic systems and detectors cannot start until the caverns are ready. Critical site preparations such as safety and reliability refurbishments for the underground infrastructure as well as a waste-rock handling system must be completed before excavation can begin. CD-3A approval for excavation of the underground equipment caverns at SURF was approved September 1, 2016. The FY 2019 Request of $113,000,000 will support the excavation of the underground equipment caverns and connecting drifts (tunnels), and support continued design work for the near site, cryogenic systems, and the DUNE detectors.

Muon to Electron Conversion Experiment (Mu2e)

Mu2e, under construction at Fermilab, will search for evidence that a muon can change directly into an electron, a process that probes energy scales beyond the collision energy of the Large Hadron Collider. If observed, this major discovery would signal the existence of new particles or new forces beyond the Standard Model. The Mu2e project completed its technical design phase (CD-3) on July 14, 2016 and moved into full construction at that time. Civil construction of the underground detector housing and the surface building for the experiment were completed in 2017. The FY 2019 Request of $30,000,000 will conclude the planned funding for this project and will support the completion of the procurements and equipment installation.

Activities and Explanation of Changes

FY 2017 Enacted	FY 2019 Request	Explanation of Changes FY 2019 Request vs FY 2017 Enacted
Construction $93,500,000	**$143,000,000**	**+$49,500,000**
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment $50,000,000	**$113,000,000**	**+$63,000,000**
Funding supported the completion of site preparation activities, and initiated the procurement of civil construction for excavation of the underground equipment caverns. Funding supported design activities for the cryogenics system, detectors, and neutrino beam.	The FY 2019 Request will support the far site civil construction for the excavation of the underground equipment caverns and connecting drifts (tunnels). In addition, the project will continue to do design work for the near site, cryogenic systems, and the DUNE detectors.	Far site civil construction for the excavation of the caverns will ramp up to its full level in FY 2019. The excavation will take approximately four years to complete.
11-SC-41, Muon to Electron Conversion Experiment $43,500,000	**$30,000,000**	**-$13,500,000**
Funding supported the continued accelerator modifications and procurement of technical components for the experiment.	The FY 2019 Request will support the completion of the procurements and the beginning of equipment installation.	FY 2019 will be the last year of funding for this line item construction project, and support will be in accordance with the approved funding plan.

High Energy Physics
Performance Measures

In accordance with the GPRA Modernization Act of 2010, the Department sets targets for, and tracks progress toward, achieving performance goals for each program.

	FY 2017	FY 2018	FY 2019
Performance Goal (Measure)	**HEP Construction/MIE Cost & Schedule - Cost-weighted mean percentage variance from established cost and schedule baselines for major construction, upgrade, or equipment procurement projects**		
Target	< 10 %	< 10 %	< 10 %
Result	Met	TBD	TBD
Endpoint Target	Adhering to the cost and schedule baselines for a complex, large scale, science project is critical to meeting the scientific requirements for the project and for being good stewards of the taxpayers' investment in the project.		
Performance Goal (Measure)	**HEP Facility Operations - Average achieved operation time of HEP user facilities as a percentage of total scheduled annual operation time**		
Target	≥ 80 %	≥ 80 %	≥ 80 %
Result	Met	TBD	TBD
Endpoint Target	Many of the research projects that are undertaken at the Office of Science's scientific user facilities take a great deal of time, money, and effort to prepare and regularly have a very short window of opportunity to run. If the facility is not operating as expected the experiment could be ruined or critically setback. In addition, taxpayers have invested millions or even hundreds of millions of dollars in these facilities. The greater the period of reliable operations, the greater the return on the taxpayers' investment.		
Performance Goal (Measure)	**HEP Neutrino Model - Carry out series of experiments to test the standard 3-neutrino model of mixing**		
Target	Fermilab switches operations mode over from neutrino beam to antineutrino beam delivery to the NOvA experiment. NOvA accumulates physics data in antineutrino mode.	MicroBooNE data taking will complete final year of phase-1. NOvA will publish the first muon and electron anti-neutrino oscillation results. ICARUS data taking will begin. SBND physics commissioning will continue.	NOvA will present important results on whether neutrino mixing is "maximal" and the mass ordering of neutrino states. MicroBooNE will address the low-energy anomalies observed in neutrino interactions. First results from ICARUS will be presented.

	FY 2017	FY 2018	FY 2019
Result	Met	TBD	TBD
Endpoint Target	Similar to quarks, the mixing between neutrinos is postulated to be described by a unitary matrix. Measuring the independent parameters of this matrix in different ways and with adequate precision will demonstrate whether this model of neutrinos is correct. Such a model is needed to correctly extract evidence for CP violation in the neutrino sector.		

High Energy Physics
Capital Summary ($K)

	Total	Prior Years	FY 2017 Enacted	FY 2018 Annualized CR[a]	FY 2019 Request	FY 2019 Request vs FY 2017 Enacted
Capital Operating Expenses Summary						
Capital equipment	n/a	n/a	98,946	—	106,450	+7,504
General plant projects (GPP)	n/a	n/a	7,400	—	1,500	-5,900
Accelerator improvement projects (AIP) (<$5M)	n/a	n/a	7,925	—	7,700	-225
Total, Capital Operating Expenses	**n/a**	**n/a**	**114,271**	—	**115,650**	**+1,379**
Capital Equipment						
Major items of equipment[b]						
Energy Frontier Experimental Physics						
LHC ATLAS Detector Upgrades[c]	20,821	12,321	8,500	—	0	-8,500
LHC CMS Detector Upgrades[d]	22,629	14,662	7,967	—	0	-7,967
HL-LHC Accelerator Upgrade Project[e]	200,000	0	0	—	42,000	+42,000
HL-LHC ATLAS Detector Upgrade[f]	128,485	0	0	—	17,500	+17,500
HL-LHC CMS Detector Upgrade[g]	128,500	0	0	—	17,500	+17,500
Intensity Frontier Experimental Physics						
Muon g-2 Experiment[h]	27,549	21,200	6,349	—	0	-6,349

[a] A full-year 2018 appropriation for this account was not enacted at the time the budget was prepared; therefore, the budget assumes this account is operating under the Continuing Appropriations Act, 2018 (Division D of P.L. 115-56, as amended). The amounts included for 2018 reflect the annualized level provided by the continuing resolution. (These amounts are shown only at the Congressional control level and above; below that level, a dash (—) is shown).

[b] Each MIE located at a DOE facility Total Estimated Cost (TEC) > $5M and each MIE not located at a DOE facility TEC > $2M.

[c] Critical Decisions CD-2 and 3 for the LHC ATLAS Detector Upgrade Project were approved on November 12, 2014. The TPC is $33,250,000.

[d] Critical Decisions CD-2 and 3 for the LHC CMS Detector Upgrade Project were approved on November 12, 2014. The TPC is $33,217,000.

[e] Critical Decision CD-1/3a for HL-LHC Accelerator Upgrade Project was approved October 13, 2017. The estimated cost range was $208,600,000 to $252,400,000.

[f] Critical Decision CD-0 for HL-LHC ATLAS Detector Upgrade Project was approved April 13, 2016. The estimated cost range was $125,000,000 to $155,000,000.

[g] Critical Decision CD-0 for HL-LHC CMS Detector Upgrade Project was approved April 13, 2016. The estimated cost range was $125,000,000 to $155,000,000.

[h] Critical Decision CD-4 for Muon g-2 Experiment was approved January 16, 2018. The TPC is $46,400,000.

	Total	Prior Years	FY 2017 Enacted	FY 2018 Annualized CR[a]	FY 2019 Request	FY 2019 Request vs FY 2017 Enacted
Cosmic Frontier Experimental Physics						
Large Synoptic Survey Telescope Camera (LSSTcam)[a]	150,300	95,500	45,000	—	0	-45,000
Dark Energy Spectroscopic Instrument[b] (DESI)	45,450	10,300	12,000	—	7,500	-4,500
LUX-ZEPLIN[c] (LZ)	52,050	11,000	12,500	—	14,450	+1,950
SuperCDMS-SNOLAB[d]	18,725	2,375	3,400	—	5,000	+1,600
Advanced Technology R&D						
FACET II[e]	17,400	0	500	—	2,000	+1,500
Total MIEs	n/a	n/a	96,216	—	105,950	+9,734
Total Non-MIE Capital Equipment	n/a	n/a	2,730	—	500	-2,230
Total, Capital equipment	**n/a**	**n/a**	**98,946**	—	**106,450**	**+7,504**
General Plant Projects (GPP)						
Industrial Center Building addition	8,250	0	6,750	—	0	-6,750
Central Utility Building (CUB) Improvement	8,839	0	0	—	1,500	+1,500
Other projects under $5 million TEC	n/a	n/a	650	—	0	-650
Total, Plant Project (GPP)	**n/a**	**n/a**	**7,400**	—	**1,500**	**-5,900**

[a] Critical Decision CD-3 for the LSSTcam project was approved on August 27, 2015. The TPC is $168,000,000.

[b] Critical Decision CD-3 for DESI project was approved on June 22, 2016, with a TPC of $56,328,000.

[c] Critical Decision CD-3 for LZ project was approved February 9, 2017. The TPC is $55,500,000.

[d] The estimated cost range for SuperCDMS-SNOLAB at Critical Decision CD-1 approved December 21, 2015 was $16,000,000–$21,500,000.

[e] The estimated cost range for FACET II at CD-1 approved on December 21, 2015 was $46,000,000–$60,000,000. Funding at the proposed FY 2019 request level would require an evaluation of the project scope from CD-1.

	Total	Prior Years	FY 2017 Enacted	FY 2018 Annualized CR[a]	FY 2019 Request	FY 2019 Request vs FY 2017 Enacted
Accelerator Improvement Projects (AIP)						
Muon Campus Cryogenics	9,600	8,200	1,400	—	0	-1,400
Sector 10 Injector Infrastructure	5,025	0	3,525	—	0	-3,525
20TW CO2 Laser Upgrade	9,000	0	0	—	500	+500
NuMI Target System	6,100	0	0	—	3,700	+3,700
Booster Intensity	6,200	0	0	—	3,000	+3,000
Bella Second Beamline	7,795	0	0	—	500	+500
Other projects under $5 million TEC[a]	n/a	n/a	3,000	—	0	-3,000
Total, Accelerator Improvement Projects	**n/a**	**n/a**	**7,925**	—	**7,700**	**-225**

[a] ATF II Upgrade was previously estimated to be $5,000,000 and was listed as a separate line in the FY 2018 Congressional submission. The project was completed under budget in FY 2017 and is now included in the Other projects under $5 Million TEC line.

Major Items of Equipment Descriptions

Energy Frontier Experimental Physics MIEs:

The *LHC ATLAS Detector Upgrade Project* was baselined (CD-2) and approved on November 12, 2014, for a fabrication start (CD-3), with a total project cost of $33,250,000 and a project completion date in FY 2019. The U.S. scope includes upgrades to the muon subsystem, the liquid-argon calorimeter detector, and the trigger and data acquisition system to take advantage of the increased LHC luminosity. The project is producing subsystem components for installation beginning in 2018. The FY 2019 Request will not include funding for this project, as it will have sufficient funds to complete all remaining deliverables.

The *LHC CMS Detector Upgrade Project* was baselined (CD-2) and approved on November 12, 2014, for a fabrication start (CD-3), with a total project cost of $33,217,000 and a project completion date in FY 2020. The planned U.S. scope includes upgrades to the pixelated inner tracking detector, the hadron calorimeter detector, and the trigger system to take advantage of the increased LHC luminosity. The project has successfully installed the pixelated inner tracking detector and portions of the trigger and hadron calorimeter; the remaining components are being produced and for installation in FY 2018. The FY 2019 Request will not include funding for this project, as it will have sufficient funds to complete all remaining deliverables.

The *High Luminosity Large Hadron Collider Accelerator Upgrade Project (HL-LHC Accelerator Upgrade Project)* requested to start as a new MIE in the FY 2018 President's Budget Request with $27,000,000 of initial TEC funding. The HL-LHC Accelerator Upgrade Project received CD-1/3a approval on October 13, 2017 with an estimated cost range of $208,600,000 to $252,400,000. Following the major upgrade, the CERN LHC machine will further increase the particle collision rate by a factor of three times to explore new physics beyond the reach of the current LHC program. The project will deliver components for which the U.S. scientists have critical expertise: interaction region focusing quadrupole magnets, and special superconducting RF crab cavities that are capable of generating transverse electric fields. The magnets will be assembled at Lawrence Berkeley National Laboratory, Brookhaven National Laboratory, and Fermilab, exploiting special expertise and unique capabilities at each laboratory. The FY 2019 Request of TEC funding will be $42,000,000 supporting the production of quadrupole magnets and crab cavities.

The *High Luminosity Large Hadron Collider ATLAS Detector Upgrade Project (HL-LHC ATLAS)* will start as a new MIE in FY 2019 with $17,500,000 of initial TEC funding. The HL-LHC ATLAS Detector Upgrade Project received CD-0 approval on April 13, 2016 with an estimated cost range of $125,000,000 to $155,000,000. The ATLAS detector is expected to integrate a factor of ten higher amount of data per run, compared to the period prior to the HL-LHC upgrades, making the physical conditions in which the detectors run very challenging. To operate for an additional decade in these new conditions, the ATLAS detector will require upgrades to the silicon pixel and strip tracker detectors, the muon detector systems, the calorimeter detectors and associated electronics, and the trigger and data acquisition systems. The National Science Foundation (NSF) is preparing a Major Research Equipment and Facility Construction (MREFC) Project to provide different scope to the HL-LHC ATLAS detector. DOE and NSF are coordinating their contributions to avoid duplication. The FY 2019 Request of TEC funding will be $17,500,000 supporting the procurement of solid-state detecting components for the ATLAS inner tracking detectors.

The *High Luminosity Large Hadron Collider CMS Detector Upgrade Project (HL-LHC CMS)* will start as a new MIE in FY 2019 with $17,500,000 of initial TEC funding. The HL-LHC CMS Detector Upgrade Project received CD-0 approval on April 13, 2016 with an estimated cost range of $125,000,000 to $155,000,000. The CMS detector is expected to integrate a factor of ten higher amount of data per run, compared to the period prior to the HL-LHC upgrades, making the physical conditions in which the detectors run very challenging. To operate for an additional decade in these new conditions, the CMS detector will require upgrades to the silicon pixel tracker detectors, outer tracker detector, the muon detector systems, the calorimeter detectors and associated electronics, and the trigger and data acquisition systems. NSF is preparing a MREFC Project to provide different scope to the HL-LHC CMS detector. DOE and NSF are coordinating their contributions to avoid duplication. The FY 2019 Request of TEC funding will be $17,500,000 supporting the procurement of solid-state detecting components for the CMS inner tracking detectors.

Intensity Frontier Experimental Physics MIE:

The *Muon g-2 Project* completion date will be in FY 2019. The FY 2019 Request will not include funding for this project, as it will have sufficient funds to complete all remaining deliverables.

Cosmic Frontier Experimental Physics MIEs:
The *Large Synoptic Survey Telescope Camera (LSSTcam*) project received CD-2 approval on January 7, 2015, with a DOE TPC of $168,000,000 and a project completion date in FY 2022. CD-3 was approved on August 27, 2015. LSSTcam is fabricating a state-of-the-art three billion pixel digital imaging camera for the next-generation, wide-field, ground-based optical and near-infrared LSST facility, located in Chile. LSST is designed to provide deep images of half the sky every few nights, enabling study of the nature of dark energy. LSSTcam is DOE's responsibility in the collaboration with the NSF, which leads the LSST project, along with private and foreign contributions. The project is currently producing many of the camera components, which are being tested and integrated before shipment to Chile in 2020. The FY 2019 Request will not include funding for this project, as it will have sufficient funds to complete all remaining deliverables.

The *Dark Energy Spectroscopic Instrument (DESI)* project received CD-2 approval on September 17, 2015 with a TPC of $56,328,000, and a project completion date of FY 2021. CD-3 was approved on June 22, 2016. DESI will fabricate a next-generation, fiber-fed, ten-arm spectrograph to be operated on Mayall 4-meter telescope at Kitt Peak National Observatory in Arizona, with operations of the telescope supported by DOE. DESI will measure the effects of dark energy on the expansion of the universe using dedicated spectroscopic measurements and will provide a strong complement to the LSST imaging survey. The FY 2019 Request of TEC funding will be $7,500,000, which will enable the project to continue its fabrication phase, producing and testing the instrument components, along with integration of the components on the telescope.

The *LUX-ZEPLIN (LZ)* project received CD-2 approval on August 8, 2016 with a TPC of $55,500,000, and a project completion date in FY 2022. CD-3 was approved on February 9, 2017. LZ is one of two MIEs selected to meet the Dark Matter Second Generation Mission Need and the concept for the experiment was developed by a merger of the LUX and ZEPLIN collaborations from the U.S. and the U.K. respectively. The project will fabricate a detector using seven tons of liquid xenon inside a time projection chamber to search for xenon nuclei that recoil in response to collisions with an impinging flux of dark matter particles known as Weakly Interacting Massive Particles (WIMPs). The detector will be located 4,850 feet deep in the Sanford Underground Research Facility (SURF) in Lead, South Dakota. The FY 2019 Request of TEC funding will be $14,450,000, which will support final procurement, fabrication, testing, and integration of detector components at SURF. This will be the final funding request for the LZ MIE.

The *Super Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Laboratory (SuperCDMS-SNOLAB)* project received CD-1 approval on December, 21, 2015 with an estimated cost range of $16,000,000 to $21,500,000. SuperCDMS-SNOLAB is one of the two MIEs selected to meet the Dark Matter Second Generation Mission Need. The project will fabricate instrumentation that uses ultra-clean, cryogenically-cooled silicon (Si) and germanium (Ge) detectors to search for Si or Ge nuclei recoiling in response to collisions with WIMPs, and will be optimized to detect low mass WIMPs to cover a range of masses complementary to that of LZ's sensitivity. The detector will be located 2 km deep in the SNOLAB facility in Sudbury, Ontario, Canada. The FY 2019 Request of TEC funding for SuperCDMS-SNOLAB will be $5,000,000, which will enable the project, in its fabrication phase, to continue producing and testing the instrument components, along with integration of the components at SNOLAB.

Advanced Technology R&D MIE:
The *Facility for Accelerator and Experimental Tests II (FACET-II)* project started MIE fabrication in FY 2017. CD-1 was approved December 21, 2015 with an estimated cost range of $46,000,000–$60,000,000. FACET-II will succeed FACET as the world's premier beam driven plasma wakefield facility and provide intense ultra-short electron beams for other applications in accelerator and related sciences. The successful FACET program ended due to the construction of the Linac Coherent Light Source II (LCLS-II) in the portion of the SLAC tunnel used by FACET. FACET-II is being designed to deliver beams using only one third of the SLAC linac. The FY 2019 Request of TEC funding for FACET-II will be $2,000,000. In FY 2019, work will continue on fabricating the beamline components that needs to be installed during the shutdown of the linac for the LCLS-II installation.

High Energy Physics
Construction Project Summary ($K)

	Total	Prior Years	FY 2017 Enacted	FY 2018 Annualized CR[a]	FY 2019 Request	FY 2019 Request vs FY 2017 Enacted
11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment						
TEC	1,465,000	61,781	50,000	49,660	113,000	+63,000
OPC	95,000	85,625	0	—[b]	1,000	+1,000
TPC	1,560,000	121,320	50,000	51,660	114,000	+64,000
11-SC-41, Muon to Electron Conversion Experiment						
TEC	250,000	132,100	43,500	43,205	30,000	-13,500
OPC	23,677	23,677	0	—	0	0
TPC	273,677	115,677	43,500	43,205	30,000	-13,500
Total, Construction						
TEC	n/a	n/a	93,500	92,865	143,000	+49,500
OPC	n/a	n/a	0	—	1,000	+1,000
TPC	n/a	n/a	93,500	94,865	144,000	+50,500

[a] A full-year 2018 appropriation for this account was not enacted at the time the budget was prepared; therefore, the budget assumes this account is operating under the Continuing Appropriations Act, 2018 (Division D of P.L. 115-56, as amended). The amounts included for 2018 reflect the annualized level provided by the continuing resolution. (These amounts are shown only at the Congressional control level and above; below that level, a dash (—) is shown).
[b] $2,000,000 is planned for FY 2018 Annualized CR.

Funding Summary ($K)

	FY 2017 Enacted	FY 2018 Annualized CR[a]	FY 2019 Request	FY 2019 Request vs FY 2017 Enacted
Research	**347,852**	**—**	**280,130**	**-67,722**
Facilities Operations				
Scientific User Facilities Operations	136,472	—	111,150	-25,322
Other Facilities	118,690	—	99,870	-18,820
Total, Facilities Operations	**255,162**	—	**211,020**	**-44,142**
Projects				
Major Items of Equipment[b]	107,566	—	109,850	+2,284
Other Projects	5,700	—	0	-5,700
Construction[b]	108,720	—	169,000	+60,280
Total, Projects	**221,986**	—	**278,850**	**+56,864**
Total, High Energy Physics	**825,000**	**819,397**	**770,000**	**-55,000**

[a] A full-year 2018 appropriation for this account was not enacted at the time the budget was prepared; therefore, the budget assumes this account is operating under the Continuing Appropriations Act, 2018 (Division D of P.L. 115-56, as amended). The amounts included for 2018 reflect the annualized level provided by the continuing resolution. (These amounts are shown only at the Congressional control level and above; below that level, a dash (—) is shown).

[b] Includes Other Project Costs.

Scientific User Facility Operations ($K)

The treatment of user facilities is distinguished between two types: TYPE A facilities that offer users resources dependent on a single, large-scale machine; TYPE B facilities that offer users a suite of resources that is not dependent on a single, large-scale machine.

Definitions:

Achieved Operating Hours – The amount of time (in hours) the facility was available for users.

Planned Operating Hours –

- For Past Fiscal Year (PY), the amount of time (in hours) the facility was planned to be available for users.
- For Current Fiscal Year (CY), the amount of time (in hours) the facility is planned to be available for users.
- For the Budget Fiscal Year (BY), based on the proposed Budget Request the amount of time (in hours) the facility is anticipated to be available for users.

Optimal Hours – The amount of time (in hours) a facility would be available to satisfy the needs of the user community if unconstrained by funding levels.

Percent of Optimal Hours – An indication of utilization effectiveness in the context of available funding; it is not a direct indication of scientific or facility productivity.

- For BY and CY, Planned Operating Hours divided by Optimal Hours expressed as a percentage.
- For PY, Achieved Operating Hours divided by Optimal Hours.

Unscheduled Downtime Hours - The amount of time (in hours) the facility was unavailable to users due to unscheduled events. NOTE: For type “A” facilities, zero Unscheduled Downtime Hours indicates Achieved Operating Hours equals Planned Operating Hours.

	FY 2017 Enacted	FY 2018 Annualized CR[a]	FY 2019 Request	FY 2019 Request vs FY 2017 Enacted
TYPE A FACILITIES				
Fermilab Accelerator Complex	**$130,781**	**—**	**$107,200**	**-$23,581**
Number of Users	2,246	—	2,096	-150
Achieved operating hours	4,823	—	N/A	N/A
Planned operating hours	4,800	—	3,600	-1,200
Optimal hours	4,800	—	4,800	0
Percent optimal hours	100.5%	—	75.0%	-25.5%
Unscheduled downtime hours	658	—	N/A	N/A

[a] A full-year 2018 appropriation for this account was not enacted at the time the budget was prepared; therefore, the budget assumes this account is operating under the Continuing Appropriations Act, 2018 (Division D of P.L. 115-56, as amended). The amounts included for 2018 reflect the annualized level provided by the continuing resolution. (These amounts are shown only at the Congressional control level and above; below that level, a dash (—) is shown).

	FY 2017 Enacted	FY 2018 Annualized CR[a]	FY 2019 Request	FY 2019 Request vs FY 2017 Enacted
Accelerator Test Facility (BNL)	**$5,691**	—	**$3,950**	**-$1,741**
Number of Users	97	—	64	-33
Achieved operating hours	2,273	—	N/A	N/A
Planned operating hours	2,060	—	1,751	-309
Optimal hours	2,500	—	2,050	-450
Percent optimal hours	90.9%	—	85.4%	-5.5%
Unscheduled downtime hours	256	—	N/A	N/A
Total Facilities	**$136,472**	—	**$111,150**	**-$25,322**
Number of Users	2,343	—	2,160	-183
Achieved operating hours	7,096	—	N/A	N/A
Planned operating hours	6,860	—	5,351	-1,509
Optimal hours	7,300	—	6,850	-450
Percent of optimal hours[a]	100.1%	—	75.4%	-24.7%
Unscheduled downtime hours	914	—	N/A	N/A

Scientific Employment

	FY 2017 Enacted	FY 2018 Annualized CR[b]	FY 2019 Request	FY 2019 Request vs FY 2017 Enacted
Number of permanent Ph.D.'s (FTEs)	895	—	740	-155
Number of postdoctoral associates (FTEs)	335	—	260	-75
Number of graduate students (FTEs)	495	—	395	-100
Other[c]	1,870	—	1,785	-85

[a] For total facilities only, this is a "funding weighted" calculation FOR ONLY TYPE A facilities: $\frac{\sum_1^n[(\%OH\ for\ facility\ n)\times(funding\ for\ facility\ n\ operations)]}{Total\ funding\ for\ all\ facility\ operations}$

[b] A full-year 2018 appropriation for this account was not enacted at the time the budget was prepared; therefore, the budget assumes this account is operating under the Continuing Appropriations Act, 2018 (Division D of P.L. 115-56, as amended). The amounts included for 2018 reflect the annualized level provided by the continuing resolution. (These amounts are shown only at the Congressional control level and above; below that level, a dash (—) is shown).

[c] Includes technicians, engineers, computer professionals, and other support staff.

11-SC-40, Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE)
Fermi National Accelerator Laboratory, Batavia, Illinois
Project is for Design and Construction

1. Significant Changes and Summary

Significant Changes

This Construction Project Data Sheet (CPDS) is an update of the FY 2018 CPDS and does not include a new start for FY 2019.

Development of the design and cost estimates have been refined since the FY 2018 Budget Request to Congress, resulting in an increase to the TPC point estimate from $1,536,000 to $1,560,000 as the U.S. DOE contributions to the multinational effort are now better understood. Additional design activities and prototypes have been identified by the project team and are being incorporated in development of the project design. A Construction Manager/General Contractor (CM/GC) was selected in FY 2017 for delivery of the Far Site conventional facilities scope that was approved at the end of FY 2016.

Summary

The FY 2019 Request for Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) is $113,000,000. The most recent approved DOE Order 413.3B is CD-3A, approval for Initial Far Site Construction: initiating excavation and construction for the LBNF Far Site conventional facilities in order to mitigate risks and minimize delays for providing a facility ready to accept detectors for installation. CD-3A was approved September 1, 2016 with a preliminary total project cost (TPC) range of $1,260,000,000 to $1,860,000,000 and CD-4 date of 4Q FY 2030. The range includes the full cost of the LBNF host facility excluding foreign contributions, as well as the full cost of the DOE contribution to the DUNE experimental apparatus.

The LBNF/DUNE construction project is a federal, state, private, and international partnership developing and implementing the technologies of particle accelerators and detectors to enable world-leading research into the fundamental physics of neutrinos, which are the most ubiquitous particles in the universe while at the same time among the most mysterious. Neutrinos are intimately involved in nuclear decay processes and high energy nuclear reactions. LBNF/DUNE will study the transformations of muon neutrinos that occur as they travel to a large detector in South Dakota, 800 miles away from Fermilab where they are produced in a high-energy beam. The experiment will analyze the rare, flavor-changing transformations of neutrinos in flight, from one lepton flavor to another, which are expected to help explain the fundamental physics of neutrinos and the puzzling matter-antimatter asymmetry that enables our existence in a matter-dominated universe.

The LBNF/DUNE project comprises a national flagship particle physics initiative. LBNF/DUNE will be the first-ever large-scale international science facility hosted by the United States. As part of implementation of High Energy Physics Advisory Panel-Particle Physics Project Prioritization Panel (P5) recommendations, the LBNF/DUNE project consists of two multinational collaborative efforts:

- LBNF is responsible for the beamline at Fermilab and other experimental and civil infrastructure at Fermilab and at the Sanford Underground Research Facility (SURF) in South Dakota. It is currently operated by the South Dakota Science and Technology Authority (SDSTA), an agency of the State of South Dakota, and hosts experiments supported by DOE, NSF, and major research universities.

  DOE entered into a land lease with the SDSTA on May 20, 2016 covering the area on which the DOE funded facilities will be housed and the LBNF and DUNE detector will be built. The lease provides the framework for DOE and Fermilab to construct federally funded buildings and facilities on non-federal land, and to establish a long-term (multi-decade) arrangement for DOE and Fermilab to use SDSTA space to host the neutrino detector. Other Project Costs (OPC) funding has been identified in years FY 2018-FY 2026 for plant support costs provided by SDSTA.

- DUNE is an international scientific collaboration responsible for defining the scientific goals & technical requirements for the beam and detectors, as well as the design, construction & commissioning of the detectors and subsequent research program.

DOE's High Energy Physics program manages both activities as a single, line-item construction project—LBNF/DUNE. LBNF, with DOE/Fermilab leadership and minority participation by a small number of international partners including CERN, will construct a megawatt-class neutrino source and related facilities at Fermilab (the "near site"), as well as underground caverns and cryogenic facilities in South Dakota (the "far site) needed to house the DUNE detectors. DUNE has international leadership and participation by about 1,000 scientists and engineers from over 160 institutions in over 30 countries. The mass of the detectors totaling 40 kilotons will be distributed in four cryostats housed in large caverns at SURF. An additional cavern at SURF will accommodate the cryogenic and other utility systems. DOE will fund less than a third of DUNE. Development of the design and cost estimates have been refined and the U.S. DOE contributions to the multinational effort are now better understood. Additional design activities and prototypes have been identified.

Contributions from the international partners to LBNF/DUNE are currently being negotiated by Fermilab and DOE. The DOE and CERN signed an agreement in May 2017 that CERN will provide in-kind contributions worth $165,000,000 for LBNF/DUNE. In September 2017, the United Kingdom announced an $88,000,000 grant to a UK collaboration that will provide in-kind contributions to LBNF/DUNE and the Proton Improvement Plan II project. The detailed distribution between the projects is still being finalized. For the DUNE detectors, the collaboration has put in place a process to complete a technical design of the detectors and divide the work of building the detectors between the collaborating institutions. The first review of the design will take place in summer of 2018 and the final design report with a complete set of funding responsibilities will be reviewed by the Long Baseline Neutrino Committee in spring of 2019. All DOE contributions to the facility and the detectors will be managed according to DOE Order 413.3B, and Fermilab will provide unified project management reporting.

Fermilab has initiated site preparation at SURF with maintenance and refurbishment activities to the mine shaft, hoists, ventilation systems, and general support infrastructure to allow for safe and reliable access prior to initiating excavation and underground construction.

The FY 2019 Request will support the far site civil construction for the excavation of the underground equipment caverns and connecting drifts (tunnels), which will be initiated late in FY 2018 and will ramp up to its full level in FY 2019. The excavation will take approximately four years to complete.

A Federal Project Director with a certification level 4 has been assigned to this project and has approved this CPDS.

2. Critical Milestone History

(fiscal quarter or date)

	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	D&D Complete	CD-4
FY 2011	1/8/2010		1Q FY 2011	TBD	4Q FY 2013	TBD	TBD	TBD
FY 2012	1/8/2010		2Q FY 2012	TBD	2Q FY 2015	TBD	TBD	TBD
FY 2016[a]	1/8/2010	12/10/2012	12/10/2012	4Q FY 2017	4Q FY 2019	4Q FY 2019	N/A	4Q FY 2027
FY 2017	1/8/2010	11/5/2015[b]	11/5/2015[b]	1Q FY 2020	1Q FY 2020	1Q FY 2020	N/A	4Q FY 2030
FY 2018	1/8/2010	11/5/2015[b]	11/5/2015[b]	1Q FY 2021	1Q FY 2022	1Q FY 2022	N/A	4Q FY 2030
FY 2019	1/8/2010	11/5/2015[b]	11/5/2015[b]	1Q FY 2021	1Q FY 2022	1Q FY 2022	N/A	4Q FY 2030

CD-0 – Approve Mission Need
Conceptual Design Complete – Actual date the conceptual design was completed
CD-1 – Approve Design Scope and Project Cost and Schedule Ranges
CD-2 – Approve Project Performance Baseline
Final Design Complete – Estimated date the project design will complete
CD-3 – Approve Start of Construction
D&D Complete – Completion of D&D work (see section 9)
CD-4 – Approve Start of Operations or Project Closeout

(fiscal quarter or date)

	CD-1R	CD-3A	CD-3B	CD-3(C)	Performance Baseline Validation
FY 2017	11/5/2015	2Q FY 2016	3Q FY 2018	1Q FY 2020	1Q FY 2020
FY 2018	11/5/2015	9/1/2016	1Q FY 2021	1Q FY 2022	1Q FY 2021
FY 2019	11/5/2015	9/1/2016	1Q FY 2021	1Q FY 2022	1Q FY 2021

CD-1R – Refresh of CD-1 approval for the new Conceptual Design.
CD-3A – Approve Initial Far Site Construction: initiating excavation and construction for the LBNF Far Site conventional facilities in order to mitigate risks and minimize delays for providing a facility ready to accept detectors for installation.
CD-3B – Approve Start of Far Site Construction: procurement of the remaining Far Site scope for conventional facilities, cryogenic systems and detectors.
CD-3(C) – Approve Start of Near Site Construction: procurement of Near Site scope and any remaining LBNF/DUNE scope. (Same as CD-3.)

[a] No CPDS was submitted for FY 2013, FY 2014 or FY 2015 because no TEC funds were requested; however, design funds were provided in each year's appropriation.
[b] Critical Decision CD-1 was approved for the new conceptual design by an ESAAB approval (CD-1R) on November 5, 2015.

3. Project Cost History

(dollars in thousands)

	TEC, Design	TEC, Construction	TEC, Total	OPC Except D&D	OPC, D&D	OPC, Total	TPC
FY 2011	102,000	TBD	TBD	22,180	TBD	TBD	TBD
FY 2012	133,000	TBD	TBD	42,621	TBD	TBD	TBD
FY 2016[a]	127,781	655,612	783,393	89,539	N/A	89,539	872,932
FY 2017	123,781	1,290,680	1,414,461	85,539	N/A	85,539	1,500,000
FY 2018	234,375	1,199,000	1,433,375	102,625	N/A	102,625	1,536,000
FY 2019[bc]	231,000	1,234,000	1,465,000	95,000	N/A	95,000	1,560,000

4. Project Scope and Justification

Scope

LBNF/DUNE will be composed of a neutrino beam created by new construction as well as modifications to the existing Fermilab accelerator complex, massive neutrino detectors (at least 40,000 tons in total) and associated cryogenics infrastructure located in one or more large underground caverns to be excavated at least 800 miles "downstream" from the neutrino source, and a much smaller neutrino detector at Fermilab for monitoring the neutrino beam near its source. A primary beam of protons will produce a neutrino beam directed into a target for converting the protons into a secondary beam of particles (pi mesons and muons) that decay into neutrinos, followed by a decay tunnel hundreds of meters long where the decay neutrinos will emerge and travel through the earth to the massive detector. The Neutrinos at the Main Injector (NuMI) beam at Fermilab is an existing example of this type of configuration for a neutrino beam facility. The new LBNF beam line will provide a neutrino beam of lower energy and greater intensity than the NuMI beam, and would point to a far detector at a greater distance than is used with NuMI experiments.

For the LBNF/DUNE project, Fermilab will be responsible for design, construction and operation of the major components of LBNF including: the primary proton beam, neutrino production target, focusing structures, decay pipe, absorbers and corresponding beam instrumentation; the conventional facilities and experiment infrastructure on the Fermilab site required for the near detector; and the conventional facilities and experiment infrastructure at SURF for the large detectors including the cryostats and cryogenics systems.

Justification

Recent international progress in neutrino physics, celebrated by the Nobel Prizes for Physics in 1988, 1995, 2002, and 2015, provides the basis for further discovery opportunities. Determining relative masses and mass ordering of the three known neutrinos will give guidance and constraints to theories beyond the Standard Model of particle physics. The study and observation of the different behavior of neutrinos and antineutrinos will offer insight into the dominance of matter over antimatter in our universe and therefore, the very structure of our universe. The only other source of the matter-antimatter asymmetry, in the quark sector, is too small to account for the observed matter dominance.

Among the technical issues addressed in the alternatives analysis were the preferred detector technology and the neutrino beamline design. After a thorough study, both technologies were found to be capable of meeting the performance requirements if located underground, only liquid argon could work on the surface, and is less expensive. A low energy

[a] No CPDS was submitted for FY 2013, FY 2014 or FY 2015 because no TEC funds were requested; however, design funds were provided in each year's appropriation.
[b] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 is $1,260,000,000 to $1,860,000,000. The TPC point estimate is $1,560,000,000.
[c] No construction, other than site preparation, approved civil construction or long-lead procurement will be performed prior to validation of the Performance Baseline and approval of CD-3.

neutrino beam to SURF and the current NuMI beam were compared. The new LBNF beam with its lower energy and longer distance to the detector was shown to be superior.

The preliminary Key Performance Parameters (KPPs) for project completion that were approved by CD-1 in FY 2015 include the primary beam and neutrino beam production systems as well as underground caverns excavated for four separate, 10 kton detectors (of liquid-argon, time-projection detectors) at the SURF site, 1000-1500 km from the neutrino source. The DOE contribution for DUNE will include technical components for two of the four detectors, which will be installed and tested with cosmic rays, and components of the cryogenic systems for the detectors, which will be installed and pressure tested. The KPPs will be finalized at CD-2.

Preliminary Key Performance Parameters

Scope	Threshold KPP	Objective KPP
Primary Beam to produce neutrinos directed to the far detector site	Beamline hardware commissioning complete and demonstration of protons delivered to the target	In addition to Threshold KPPs, system enhancements to maximize neutrino flux, enable tunability in neutrino energy spectrum or to improve neutrino beam capability
Far Site-Conventional Facilities	Caverns excavated for 40 kiloton fiducial detector mass[a]; beneficial occupancy granted for cavern space to house 20 kiloton fiducial detector mass[a]	In addition to Threshold KPPs, Beneficial Occupancy granted for remaining cavern space
Detector Cryogenic Infrastructure	DOE-provided components for Cryogenic subsystems installed and pressure tested for 20 kiloton fiducial detector mass	In addition to Threshold KPPs, additional DOE contributions to cryogenic subsystems installed and pressure tested for additional 20 kiloton fiducial detector mass; DOE contributions to cryostats
Long-Baseline Distance between neutrino source and far detector	1,000-1,500 kilometers	1,000-1,500 kilometers
Far Detector	DOE-provided components installed in cryostats to support 20 kiloton fiducial detector mass, with cosmic ray interactions detected in each detector module	In addition to Threshold KPPs, additional DOE contributions to support up to 40 kiloton fiducial detector mass

[a] Fiducial detector mass pertains to the mass of the interior volume of the detection medium (liquid argon) that excludes the external portion of the detection medium where most background events would occur.

5. Financial Schedule[a]

	(dollars in thousands)			
	Appropriations	Obligations	Recovery Act Costs	Costs[b]
Total Estimated Cost (TEC)				
Design Only[c]				
FY 2012	4,000	4,000	0	0[d]
FY 2013	3,781	3,781	0	801
FY 2014	16,000	16,000	0	7,109
FY 2015	12,000	12,000	0	15,791
FY 2016	0	0	0	12,080
Subtotal, Design Only	35,781	35,781	0	35,781
Design (Design and Construction)				
FY 2016	N/A	N/A	0	14,356[e]
FY 2017	N/A	N/A	0	37,257
FY 2018	N/A	N/A	0	11,000[f]
FY 2019	N/A	N/A	0	20,000
Outyears	N/A	N/A	0	112,606
Subtotal, Design (Design and Construction)	N/A	N/A	0	195,219
Total, Design	N/A	N/A	0	231,000
Construction				
FY 2017	N/A	N/A	0	13,000
FY 2018	N/A	N/A	0	43,900[g]
FY 2019	N/A	N/A	0	93,000
Outyears	N/A	N/A	0	1,084,100
Total, Construction	N/A	N/A	0	1,234,000

[a] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 is $1,260,000,000 to $1,860,000,000. The TPC point estimate is $1,560,000,000. Design and international collaboration plans are currently being developed; outyears are preliminary.
[b] Costs through FY 2017 reflect actual costs; costs for FY 2018 and the outyears are estimates.
[c] Design Only CPDS was prepared in FY 2012; no CPDS was prepared FY 2013-2015. Funding amounts shown for traceability. FY 2016 and onward CPDS prepared as Design and Construction.
[d] $1,078,000 was erroneously costed to this project in FY 2012, the accounting records were adjusted in early FY 2013.
[e] Costs were for Far Site preparation including safety and reliability refurbishment of the underground infrastructure, which is needed prior to initiating excavation of the equipment caverns.
[f] Estimated costs are for continuing project engineering design in preparation for CD-2.
[g] Estimated costs are for initiating excavation of the equipment caverns at the Far Site as approved by CD-3A.

	(dollars in thousands)			
	Appropriations	Obligations	Recovery Act Costs	Costs[b]
TEC				
FY 2012	4,000	4,000	0	0
FY 2013	3,781	3,781	0	801
FY 2014	16,000	16,000	0	7,109
FY 2015	12,000	12,000	0	15,791
FY 2016	26,000	26,000	0	26,436
FY 2017	50,000	50,000	0	50,257
FY 2018	54,900	54,900	0	54,900
FY 2019	113,000	113,000	0	113,000
Outyears	1,185,319	1,185,319	0	1,196,706
Total, TEC	1,465,000	1,465,000	0	1,465,000
Other Project Cost (OPC)				
OPC except D&D				
FY 2009 Recovery Act	12,486[a]	12,486	0	0
FY 2010	14,178	14,178	4,696	6,336
FY 2011	7,768	7,750	7,233	11,321
FY 2012	17,000	17,018[b]	557[c]	17,940
FY 2013	14,107	14,107	0	13,232
FY 2014	10,000	10,000	0	11,505
FY 2015	10,000	10,000	0	10,079
FY 2016	86	86	0	2,284
FY 2017	0	0	0	120
FY 2018	100	100	0	100
FY 2019	1,000	1,000	0	1,000
Outyears	8,275	8,275	0	8,597
Total, OPC	95,000	95,000	12,486	82,514
Total Project Cost (TPC)				
FY 2009 Recovery Act	12,486	12,486	0	0
FY 2010	14,178	14,178	4,696	6,336
FY 2011	7,768	7,750	7,233	11,321
FY 2012	21,000	21,018	557	17,940
FY 2013	17,888	17,888	0	14,033
FY 2014	26,000	26,000	0	18,614
FY 2015	22,000	22,000	0	25,870

[a] $13,000,000 of Recovery Act funding was originally planned for the conceptual design; the difference of $512,000 relates to pre-conceptual design activities needed prior to approval of mission need (CD-0).
[b] $18,000 of FY 2011 funding was attributed towards the Other Project Costs activities in FY 2012.
[c] During FY 2012, $1,000 of Recovery Act funding was recategorized from pre-conceptual design and so became part of the OPC. $3,000 was deobligated and expired because Recovery Act funds are no longer available for obligation.

	(dollars in thousands)			
	Appropriations	Obligations	Recovery Act Costs	Costs[b]
FY 2016	26,086	26,086	0	28,720
FY 2017	50,000	50,000	0	50,377
FY 2018	55,000	55,000	0	55,000
FY 2019	114,000	114,000	0	114,000
Outyears	1,193,594	1,193,594	0	1,205,303
Total, TPC	1,560,000	1,560,000	12,486	1,547,514

6. Details of Project Cost Estimate

	(dollars in thousands)		
	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design			
Design	208,000	201,375	N/A
Contingency	23,000	33,000	N/A
Total, Design	231,000	234,375	N/A
Construction			
Far Site Civil Construction[a]	360,375	300,000	N/A
Fermilab Site Civil Construction[b]	317,375	281,000	N/A
Far Site Technical Infrastructure[c]	108,125	98,000	N/A
Fermilab Site Beamline[c]	125,125	110,000	N/A
DUNE Detectors	82,000	75,000	N/A
Contingency	241,000	335,000	N/A
Total, Construction	1,234,000	1,199,000	N/A
Total, TEC	1,465,000	1,433,375	N/A
Contingency, TEC	264,000	368,000	N/A
Other Project Cost (OPC)			
OPC except D&D			
R&D	20,625	20,625	N/A
Conceptual Planning	30,000	30,000	N/A
Conceptual Design	35,000	35,000	N/A
Plant Support Costs	9,375	17,000	N/A
Total, OPC	95,000	102,625	N/A
Total, TPC	1,560,000	1,536,000	N/A
Total, Contingency	264,000	368,000	N/A

[a] Far Site civil construction involves excavation of caverns at SURF, 4850 ft. below the surface, for technical equipment including particle detectors and cryogenic systems.
[b] Fermilab Site civil construction involves construction of the housing for the neutrino-production beam line and the near detector.
[c] Technical equipment in the DOE scope, estimated here, will be supplemented by in-kind contributions of additional technical equipment, for the accelerator beam and particle detectors, from non-DOE partners as described in Section 1.

7. Schedule of Appropriation Requestsa

Request Year		(dollars in thousands) Prior Years	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	Outyears	Total
FY 2011	TEC	102,000	0	0	0	0	0	0	102,000
	OPC	22,180	0	0	0	0	0	0	22,180
	TPC	124,180	0	0	0	0	0	0	124,180
FY 2012	TEC	91,000	42,000	0	0	0	0	0	133,000
	OPC	42,621	0	0	0	0	0	0	42,621
	TPC	133,621	42,000	0	0	0	0	0	175,621
FY 2016	TEC	23,781	12,000	16,000	TBD	TBD	TBD	TBD	783,393
	OPC	75,539	10,000	4,000	TBD	TBD	TBD	TBD	89,539
	TPC	99,320	22,000	20,000	TBD	TBD	TBD	TBD	872,932
FY 2017	TEC	23,781	12,000	26,000	45,021	TBD	TBD	1,307,659	1,414,461
	OPC	75,539	10,000	0	0	0	TBD	0	85,539
	TPC	99,320	22,000	26,000	45,021	TBD	TBD	1,307,659	1,500,000
FY 2018	TEC	23,781	12,000	26,000	50,000	54,900	0	1,266,694	1,433,375
	OPC	75,539	10,000	86	0	100	0	16,900	102,625
	TPC	99,320	22,000	26,086	50,000	55,000	0	1,283,594	1,536,000
FY 2019[b]	TEC	23,781	12,000	26,000	50,000	54,900	113,000	1,185,319	1,465,000
	OPC	75,539	10,000	86	0	100	1,000	8,275	95,000
	TPC	99,320	22,000	26,086	50,000	55,000	114,000	1,193,594	1,560,000

8. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	FY 2030
Expected Useful Life	20 years
Expected Future Start of D&D of this capital asset	FY 2050

Operations and maintenance funding of this experiment will become part of the existing Fermilab accelerator facility. Annual related funding estimates include the incremental cost of 20 years of full operation, utilities, maintenance and repairs with the accelerator beam on. The estimates also include operations and maintenance for the remote site of the large detector.

(Related Funding Requirements)

(dollars in thousands)

	Annual Costs		Life Cycle Costs	
	Current Total Estimate	Previous Total Estimate	Current Total Estimate	Previous Total Estimate
Operations	9,000	9,000	180,000	180,000
Utilities	8,000	8,000	160,000	160,000
Maintenance & Repair	1,000	1,000	20,000	20,000
Total	18,000	18,000	360,000	360,000

[a] Design and international collaboration plans are currently being developed; outyears are preliminary.

[b] The project is Pre-CD-2 and has not been baselined. All estimates are preliminary. The preliminary TPC range at CD-1 was $1,260,000,000 to $1,860,000,000. The TPC point estimate is $1,560,000,000.

9. Required D&D Information

	Square Feet
Area of new construction	142,000 SF
Area of existing facility being replaced and D&D'd by this project	0
Area of other D&D outside the project	0
Area of any additional D&D space to meet the "one-for-one" requirement taken from the banked area.	142,000 SF

The one-for-one replacement has been met through banked space. A waiver from the one-for-one requirement to eliminate excess space at Fermilab to offset the LBNF/DUNE project was approved by DOE Headquarters on November 12, 2009. The waiver identified and transferred to Fermilab 575,104 square feet of excess space to accommodate the new LBNF/DUNE facilities and other as yet unbuilt facilities from space that was banked at other DOE facilities.

10. Acquisition Approach

The acquisition approach is documented in the Acquisition Strategy approved as part of CD-1. DOE is acquiring design, construction, fabrication, and operation of LBNF through the M&O contractor responsible for Fermilab, Fermi Research Alliance (FRA). FRA and Fermilab, through the LBNF Project based at Fermilab, is responsible to DOE to manage and complete construction of LBNF at both the near and remote site locations. FRA and Fermilab are assigned oversight and management responsibility for execution of the international DUNE project, to include management of the DOE contributions to DUNE. The basis for this choice and strategy is that:

- Fermilab is the site of the only existing neutrino beam facility in the U.S. and, in addition to these facilities, provides a source of existing staff and expertise to be utilized for beamline and detector construction.
- Fermilab can best ensure that the design, construction, and installation of key LBNF and DUNE components are coordinated effectively and efficiently with other research activities at Fermilab.
- Fermilab has a DOE-approved procurement system with established processes and acquisition expertise needed to obtain the necessary components and services to build the scientific hardware, equipment and conventional facilities for the accelerator beamline, and detectors for LBNF and DUNE.
- Fermilab has extensive experience in managing complex construction, fabrication, and installation projects involving multiple national laboratories, universities, and other partner institutions, building facilities both on-site and at remote off-site locations.
- Fermilab, through the LBNF Project, has established a close working relationship with SURF and the South Dakota Science and Technology Authority (SDSTA), organizations that manage and operate the remote site for the far detector in Lead, SD;
- Fermilab has extensive experience with management and participation in international projects and international collaborations, including most recently the LHC and CMS projects at CERN, as well as in the increasingly international neutrino experiments and program.

The LBNF/DUNE construction project is a federal, state, private and international partnership. Leading the LBNF/DUNE Project, Fermilab will collaborate and work with many institutions, including several DOE national laboratories (BNL, LBNL and LANL), dozens of universities, foreign research institutions, SURF, and the SDSTA. Fermilab will be responsible for overall project management, near site conventional facilities, and the beamline. Fermilab will work with SDSTA and SURF to complete the conventional facilities construction at the remote site needed to house and outfit the DUNE far detector. With the DUNE collaboration, Fermilab is also responsible for technical and resource coordination to support the DUNE far and near detector design and construction. DOE will be providing in-kind contributions to the DUNE collaboration for detector systems, as agreed upon with the international DUNE collaboration.

International participation in the design, construction, and operation of LBNF and DUNE will be of essential importance because the field of High Energy Physics is international by nature; necessary talent and expertise are globally distributed, and DOE does not have the procurement or technical resources to self-perform all of the required construction and fabrication work. Contributions from other nations will be predominantly through the delivery of components built in their own countries by their own researchers. DOE will negotiate agreements in cooperation with the Department of State on a bilateral basis with all contributing nations to specify their expected contributions and the working relationships during the construction and operation of the experiment. For the DUNE detector, the process of developing in-kind contributions is being driven by the principal investigators and being reviewed by their funding agencies.

DOE funding for the LBNF/DUNE Project will be provided directly to Fermilab and collaborating DOE national laboratories via approved financial plans, and under management control of the LBNF Project Office. The LBNF Project Office will also manage and control DOE funding to the other LBNF/DUNE institutions contributing to detector design and construction. In addition to the work performed by DOE national laboratories, a combination of university subcontracts and direct fixed-price purchases with vendors is anticipated to design, fabricate, and install the LBNF and DUNE technical components. The DUNE-U.S. Project Office at Fermilab will manage and control DOE funding to the other U.S. institutions contributing to DUNE detector design and construction. All actions will be in accordance with the DOE approved procurement policies and procedures.

Much of the neutrino beamline component design, fabrication, assembly, and installation will be done by Fermilab staff or by subcontract temporary staff working directly with Fermilab personnel. The acquisition approach includes both new procurements based on existing designs, and re-purposed equipment from the Fermilab accelerator complex. Some highly specialized components will be designed and fabricated by or in consultation with long-standing Fermilab collaborators having proven experience with such components.

Delivery of LBNF conventional facilities at the Fermilab near site and SURF far site will be via the Construction Manager/General Contractor (CM/GC) model. This strategy was chosen to reduce risk, enhance quality and safety performance, provide a more collaborative approach to construction, and offer the opportunity for reduced cost and shortened construction schedules.

For the LBNF near site conventional facilities at Fermilab, procurement is through existing Fermilab master subcontracts with national architect/engineering (A/E) companies for design services and contracts will be incrementally phase-funded since they will span multiple years.

For the LBNF far site conventional facilities at SURF, Fermilab will work with SDSTA, the owner of the site and land, which has been donated to SDSTA by the Homestake Mining Company for the sole purpose of facilitating scientific and technological research and development. Fermilab will contract directly with SDSTA to provide pre-construction services and with an A/E firm for design of LBNF far site conventional facilities at SURF. Fermilab will solicit bids for CM/GC services to manage the construction of LBNF far site facilities. The CM/GC subcontractor will furnish all labor, equipment and materials for far site conventional facilities construction management. Work includes pre-construction construction management services and an option for executing the construction and management of the construction. The CM/GC subcontractor staff will have proven experience in the area of construction management and construction of industrial and heavy construction projects. The CM/GC firm will provide support services to the LBNF and A/E teams, including input regarding the selection of materials, building systems and equipment, construction feasibility, value engineering, and factors related to construction, plus cost estimates and schedules, including estimates of alternative designs or materials. The CM/GC will also provide recommendations of actions designed to minimize adverse effects of labor or material shortages, time requirements for procurement and installation and construction completion.

The overall approach to both near and far site enables Fermilab to gain construction management expertise early in the design phase to produce well-integrated designs and well understood constructability, with potential cost and management efficiencies and reduced construction risk as a result.

DOE entered into a land lease with SDSTA on May 20, 2016 covering the area on which the DOE funded facilities housing and supporting the LBNF and DUNE detector will be built. The lease provides the framework for DOE and Fermilab to construct federally funded buildings and facilities on non-federal land, and to establish a long-term (multi-decade) arrangement for DOE and Fermilab to use SDSTA space to host the DUNE experiment. Modifications, repairs, replacements, and improvements to SDSTA infrastructure will be funded by the project to ensure safe and reliable operations of the systems required to carry out the DOE mission. Protections for DOE's real property interests in these infrastructure tasks are acquired through the lease with SDSTA, contracts and other agreements such as easements. DOE plans for Fermilab to have responsibility for managing and operating the LBNF and DUNE far detector and facilities for a useful lifetime of 20 years and may contract with SDSTA for day-to-day management and maintenance services. At the end of useful life, federal regulations permit transfer of ownership to SDSTA, which is willing to accept ownership as a condition for the lease. An appropriate decommissioning plan will be developed prior to lease signing.

11-SC-41, Muon to Electron Conversion Experiment (Mu2e),
Fermi National Accelerator Laboratory, Batavia, Illinois
Project is for Design and Construction

1. Significant Changes and Summary

Significant Changes
This Construction Project Data Sheet (CPDS) is an update of the FY 2018 CPDS and does not include a new start for FY 2019.

Summary
The FY 2019 Request for the Muon to Electron Conversion Experiment (Mu2e) is $30,000,000, consistent with the approved baseline funding profile, and is the last year of planned funding for the construction project. The most recent DOE Order 413.3B approved Critical Decision (CD) is CD-3 (Approve Start of Construction), concurrent with completion of the final design, approved on July 14, 2016. In FY 2015, CD-2 established the scope, cost, and schedule baseline, and CD-3B initiated civil construction and long-lead procurement of the Transport Solenoid modules. Total Project Cost was approved at $273,677,000. The funding profile supports this TPC. The CD-4 milestone is 1Q FY 2023.

A Federal Project Director with Certification Level 3 has been assigned to this project and has approved this CPDS.

The Mu2e project provides the accelerator beam and experimental apparatus to unambiguously identify neutrinoless muon-to-electron conversion events. The conversion of a muon to an electron in the field of a nucleus would probe new physics for discovery at mass scales far beyond the reach of any existing or proposed experiment.

Construction progressed according to plan in FY 2017. Civil construction of the building and underground housing for the experiment was completed in April 2017. This civil facility has special capabilities required to house the primary beam target and transport systems for producing the muons and stopping them in the detector system. FY 2018 and FY 2019 funding will support procurement and fabrication activities for the accelerator, beamline, superconducting magnets and particle detector technical systems will continue.

2. Critical Milestone History

(fiscal quarter or date)

	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3	D&D Complete	CD-4
FY 2011	11/24/2009		4Q FY 2010	TBD	4Q FY 2012	TBD	TBD	TBD
FY 2012	11/24/2009		4Q FY 2011	TBD	4Q FY 2013	TBD	TBD	TBD
FY 2013	11/24/2009		4Q FY 2012	4Q FY 2013	4Q FY 2014	4Q FY 2014	N/A	4Q FY 2018
FY 2014	11/24/2009		7/11/2012	2Q FY 2014	2Q FY 2015	4Q FY 2015	N/A	2Q FY 2021
FY 2013 Repro-gramming	11/24/2009		7/11/2012	2Q FY 2014	2Q FY 2015	4Q FY 2015	N/A	2Q FY 2021
FY 2015	11/24/2009		7/11/2012	4Q FY 2014	2Q FY 2015	4Q FY 2014	N/A	2Q FY 2021
FY 2016	11/24/2009	7/11/2012	7/11/2012	2Q FY 2015	3Q FY 2016	3Q FY 2016	N/A	1Q FY 2023
FY 2017 PB	11/24/2009	7/11/2012	7/11/2012	3/4/2015	3Q FY 2016	3Q FY 2016	N/A	1Q FY 2023
FY 2018	11/24/2009	7/11/2012	7/11/2012	3/4/2015	7/14/2016	7/14/2016	N/A	1Q FY 2023
FY 2019	11/24/2009	7/11/2012	7/11/2012	3/4/2015	7/14/2016	7/14/2016	N/A	1Q FY 2023

CD-0 – Approve Mission Need
Conceptual Design Complete – Actual date the conceptual design was completed
CD-1 – Approve Design Scope and Project Cost and Schedule Ranges

CD-2 – Approve Project Performance Baseline
Final Design Complete – Estimated/Actual date the project design will be/was completed
CD-3 – Approve Start of Construction
D&D Complete – Completion of D&D work (see section 9)
CD-4 – Approve Start of Operations or Project Closeout
PB – Indicates the Performance Baseline

	Performance Baseline Validation	CD-3A	CD-3B	CD-3(C)
FY 2014		3Q FY 2013		
FY 2013 Reprogramming		3Q FY 2013		
FY 2015		3Q FY 2014		
FY 2016	2Q FY 2015	7/10/2014	2Q FY 2015	3Q FY 2016
FY 2017 PB	3/4/2015	7/10/2014	3/4/2015	3Q FY 2016
FY 2018	3/4/2015	7/10/2014	3/4/2015	7/14/2016
FY 2019	3/4/2015	7/10/2014	3/4/2015	7/14/2016

CD-3A – Approve Long-Lead Procurement of superconducting wire for the magnet systems.
CD-3B – Approve Long-Lead Procurement for superconducting solenoid magnet modules and for construction of the detector hall.
CD-3(C) – Approve All Construction and Fabrication (same as CD-3)

3. Project Cost History

(dollars in thousands)

	TEC, Design	TEC, Construction	TEC, Total	OPC Except D&D	OPC, D&D	OPC, Total	TPC
FY 2011	35,000	TBD	TBD	10,000	TBD	TBD	TBD
FY 2012	36,500	TBD	TBD	18,777	TBD	TBD	TBD
FY 2013	44,000	N/A	N/A	24,177	0	24,177	68,177
FY 2014	61,000	162,000	223,000	26,177	0	26,177	249,177
FY 2013 Reprogramming	49,000	162,000	211,000	23,677	0	23,677	234,677
FY 2015	47,000	162,900	209,900	23,677	0	23,677	233,577
FY 2016	57,000	193,000	250,000	23,677	N/A	23,677	273,677
FY 2017 PB	57,000	193,000	250,000	23,677	N/A	23,677	273,677[a]
FY 2018	60,598[b]	189,402	250,000	23,677	N/A	23,677	273,677
FY 2019	60,598	189,402	250,000	23,677	N/A	23,677	273,677

4. Project Scope and Justification

Scope
The Mu2e project includes accelerator modifications, fabrication of superconducting magnets and particle detector systems, and construction of a civil facility with the special capabilities necessary for the experiment. The scope of work in the Project Data Sheet has not changed. The muon beam for the Mu2e experiment will be produced by an intense 8-GeV proton beam, extracted from the Fermilab Booster accelerator, striking a tungsten target. The Mu2e project is modifying the existing Fermilab accelerator complex (Booster, Recycler, and Debuncher Rings) to deliver the primary proton beam to a muon production target, and will efficiently collect and transport the produced muons to a stopping target. The stopping target is

[a] No construction, other than approved long-lead procurement and detector hall civil construction, was performed prior CD-3 approval.
[b] Increased final design development work in FY 2016 reduced the estimated construction cost with modest delay of final design completion and Critical Decision CD-3.

surrounded by the Mu2e detector system that can identify muon-to-electron conversions and reject background contamination from muon decays, which produce neutrinos, in contrast to muon conversions which are neutrinoless.

The project has designed and is constructing the detector system (consisting of a tracker, calorimeter, cosmic ray veto, and data acquisition subsystem), a new beam line to the detector system from the former Debuncher Ring, and three superconducting solenoid magnets (a Production Solenoid, Transport Solenoid and Detector Solenoid) that will serve as the beam transport channel for collecting the muons and transporting them into the detector system.

The project designed and completed construction of a 25,000 square foot civil facility with the special capabilities required to house the primary beam target and transport systems for producing the muons and stopping them in the detector system. The civil construction consists of an underground detector enclosure and a surface building for containing the necessary equipment and infrastructure that can be accessed while the multikilowatt proton beam is being delivered to the experiment. The building includes radiation shielding and design features for safe operation of the beam line and experimental apparatus.

Justification

The conversion of a muon to an electron in the Coulomb field of an atomic nucleus provides a unique experimental signature for discovery of charged-lepton flavor-symmetry violation (CLFV), which may be accessible to this experiment of unprecedented sensitivity and would allow access to new physics at very high mass scales beyond the reach of the LHC. In 2008, the Particle Physics Project Prioritization Panel (P5), a subpanel of the High Energy Physics Advisory Panel (HEPAP), recommended: “Development of a muon-to-electron conversion experiment should be strongly encouraged under all budget scenarios considered by the panel.”[a] Again, in 2014, the most recent P5 Subpanel emphasized the priority of the current “Mu2e” experimental construction project in its new report to HEPAP, saying the Mu2e project is an “immediate target of opportunity in the drive to search for new physics and will help inform future choices of direction.” “The scientific case is undiminished relative to its earlier prioritization.”[b]

[a] “US Particle Physics: Scientific Opportunities, A Strategic Plan for the Next 10 Years,” Report of the Particle Physics Project Prioritization Panel (May 2008).
[b] “Building for Discovery, Strategic Plan for U.S. Particle Physics in the Global Context,” Report of the Particle Physics Project Prioritization Panel (May 2014).

Key Performance Parameters

System	Threshold Performance	Objective Performance
Accelerator		
	Accelerator components are acceptance tested at nominal voltages and currents. Components necessary for single-turn extraction installed.	Protons are delivered to the diagnostic absorber in the M4 beamline.
	Shielding designed for 1.5 kW operation delivered to Fermilab and ready for installation.	Shielding designed for 8 kW operation delivered to Fermilab and ready for installation.
	All target station components are complete, delivered to Fermilab and tested. Heat and Radiation Shield is installed in Production Solenoid. Other components are ready to be installed after field mapping.	
Superconducting Solenoid Magnets		
	The Production, Transport and Detector Solenoids have been cooled and powered to the settings necessary to take physics data.	The Production, Transport and Detector Solenoids have been cooled and powered to their nominal field settings.
Detector Components		
	Cosmic Ray Tracks are observed in the Tracker, Calorimeter and a subset of the Cosmic Ray Veto and acquired by the Data Acquisition System after they are installed in the garage position behind the Detector Solenoid. The balance of the Cosmic Ray Veto counters are at Fermilab and ready for installation.	The cosmic ray data in the detectors is acquired by the Data Acquisition System, reconstructed in the online processors, visualized in the event display and stored on disk.

The project is being conducted in accordance with the project management requirements in DOE 413.3B, Program and Project Management for the Acquisition of Capital Assets.

5. Financial Schedule

	(dollars in thousands)		
	Appropriations	Obligations	Costs[a]
Total Estimated Cost (TEC)			
Design			
FY 2013	N/A	N/A	14,653
FY 2014	N/A	N/A	15,404
FY 2015	N/A	N/A	16,892
FY 2016	N/A	N/A	13,649
Total, Design	N/A	N/A	60,598
Construction			
FY 2014	N/A	N/A	0
FY 2015	N/A	N/A	9,907
FY 2016	N/A	N/A	24,300
FY 2017	N/A	N/A	26,868
FY 2018	N/A	N/A	40,000
FY 2019	N/A	N/A	40,000

[a] Costs through FY 2017 reflect actual costs; costs for FY 2018 and the outyears are estimates.

	(dollars in thousands)		
	Appropriations	Obligations	Costs[a]
FY 2020	N/A	N/A	37,132
FY 2021	N/A	N/A	10,000
FY 2022	N/A	N/A	1,195
Total, Construction	N/A	N/A	189,402
TEC			
FY 2012	24,000	24,000	0
FY 2013	8,000[a]	8,000	14,653
FY 2014	35,000[b]	35,000	15,404
FY 2015	25,000[c]	25,000	26,799
FY 2016	40,100	40,100	37,949
FY 2017	43,500	43,500	26,868
FY 2018	44,400	44,400	40,000
FY 2019	30,000	30,000	40,000
FY 2020	0	0	37,132
FY 2021	0	0	10,000
FY 2022	0	0	1,195
Total, TEC	250,000	250,000	250,000
Other Project Costs (OPC)			
OPC except D&D			
FY 2010	4,777	4,777	3,769
FY 2011	8,400	8,400	8,940
FY 2012	8,000	8,000	6,740
FY 2013	2,500	2,500	1,020
FY 2014	0	0	2,136
FY 2015	0	0	159
FY 2016	0	0	252
FY 2017	0	0	11
FY 2018	0	0	650
Total, OPC	23,677	23,677	23,677

[a] Congress approved a reprogramming that reduced the FY 2013 funding to $8,000,000 from the $22,685,000 that was originally appropriated.
[b] $5,162,907 was for long-lead procurements of superconducting wire for the magnet systems.
[c] $25,000,000 was for long-lead procurements for the superconducting solenoid magnet modules and for civil construction of the detector hall.

	(dollars in thousands)		
	Appropriations	Obligations	Costs[a]
Total Project Cost (TPC)			
FY 2010	4,777	4,777	3,769
FY 2011	8,400	8,400	8,940
FY 2012	32,000	32,000	6,740
FY 2013	10,500	10,500	15,673
FY 2014	35,000	35,000	17,540
FY 2015	25,000	25,000	26,958
FY 2016	40,100	40,100	38,201
FY 2017	43,500	43,500	26,879
FY 2018	44,400	44,400	40,650
FY 2019	30,000	30,000	40,000
FY 2020	0	0	37,132
FY 2021	0	0	10,000
FY 2022	0	0	1,195
Total, TPC	273,677	273,677	273,677

6. Details of Project Cost Estimate

	(dollars in thousands)		
	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Total Estimated Cost (TEC)			
Design			
Design	60,598	60,598	49,000
Contingency	0	0	8,000
Total, Design	60,598	60,598	57,000
Construction			
Site Work	1,390	2,000	2,000
Construction	18,477	13,000	13,000
Equipment	133,535	129,400	133,000
Contingency	36,000	45,002	45,000
Total, Construction	189,402	189,402	193,000
Total, TEC	250,000	250,000	250,000
Contingency, TEC	36,000	45,002	53,000
Other Project Cost (OPC)			
OPC except D&D			
R&D	8,200	8,200	8,200
Conceptual Planning	2,300	2,300	2,300
Conceptual Design	13,177	13,177	13,177
Total, OPC	23,677	23,677	23,677
Total, TPC	273,677	273,677	273,677
Total, Contingency	36,000	45,002	53,000

7. Schedule of Appropriation Requests

(dollars in thousands)

Request Year		Prior Years	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	Total
FY 2011	TEC	5,000	30,000	0	0	0	0	0	0	0	35,000
	OPC	10,000	0	0	0	0	0	0	0	0	10,000
	TPC	15,000	30,000	0	0	0	0	0	0	0	45,000
FY 2012	TEC	0	24,000	12,500	0	0	0	0	0	0	36,500
	OPC	12,777	6,000	0	0	0	0	0	0	0	18,777
	TPC	12,777	30,000	12,500	0	0	0	0	0	0	55,277
FY 2013	TEC	0	24,000	20,000	0	0	0	0	0	0	44,000
	OPC	13,177	6,000	5,000	0	0	0	0	0	0	24,177
	TPC	13,177	30,000	25,000	0	0	0	0	0	0	68,177
FY 2014	TEC	0	24,000	24,147	35,000	32,000	44,000	45,000	23,000	0	223,000
	OPC	13,177	8,000	8,049	0	0	0	0	0	0	26,177
	TPC	13,177	32,000	32,196[a]	35,000	32,000	44,000	45,000	23,000	0	249,177
FY 2013 Repro-gram-ming	TEC	0	24,000	8,000[b]	35,000	32,000	44,000	45,000	23,000	0	211,000
	OPC	13,177	8,000	2,500	0	0	0	0	0	0	23,677
	TPC	13,177	32,000	10,500	35,000	32,000	44,000	45,000	23,000	0	234,677
FY 2015	TEC	0	24,000	8,000	35,000	25,000	42,000	43,000	32,900	0	209,900
	OPC	13,177	8,000	2,500	0	0	0	0	0	0	23,677
	TPC	13,177	32,000	10,500	35,000	25,000	42,000	43,000	32,900	0	233,577
FY 2016	TEC	0	24,000	8,000	35,000	25,000	40,100	43,500	44,400	30,000	250,000
	OPC	13,177	8,000	2,500	0	0	0	0	0	0	23,677
	TPC	13,177	32,000	10,500	35,000	25,000	40,100	43,500	44,400	30,000	273,677
FY 2017 PB	TEC	0	24,000	8,000	35,000	25,000	40,100	43,500	44,400	30,000	250,000
	OPC	13,177	8,000	2,500	0	0	0	0	0	0	23,677
	TPC	13,177	32,000	10,500	35,000	25,000	40,100	43,500	44,400	30,000	273,677
FY 2018	TEC	0	24,000	8,000	35,000	25,000	40,100	43,500	44,400	30,000	250,000
	OPC	13,177	8,000	2,500	0	0	0	0	0	0	23,677
	TPC	13,177	32,000	10,500	35,000	25,000	40,100	43,500	44,400	30,000	273,677
FY 2019	TEC	0	24,000	8,000	35,000	25,000	40,100	43,500	44,400	30,000	250,000
	OPC	13,177	8,000	2,500	0	0	0	0	0	0	23,677
	TPC	13,177	32,000	10,500	35,000	25,000	40,100	43,500	44,400	30,000	273,677

[a] The FY 2013 amount shown reflected the P.L. 112-175 continuing resolution level annualized to a full year. The TEC, OPC, and TPC total and outyear appropriation assumptions were not adjusted to reflect the final FY 2013 level; the FY 2013 Request level of $25,000,000 ($20,000,000 TEC and $5,000,000 OPC) were assumed instead.

[b] Congress approved a reprogramming that reduced the FY 2013 funding to $8,000,000 from the $22,685,000 that was originally appropriated.

8. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy	FY 2023
Expected Useful Life	10 years
Expected Future Start of D&D of this capital asset	FY 2033

Operations and maintenance of this experiment will become part of the existing Fermilab accelerator facility. Annual related funding estimates are for the incremental cost of five years of full operation, utilities, maintenance and repairs with the accelerator beam on. Five subsequent years are planned for further analysis of the data while the detector and beam line are maintained in a minimal maintenance state (with annual cost of approximately 3% of full operations) to preserve availability for future usage with much smaller annual cost.

(Related Funding Requirements)

(dollars in thousands)

	Annual Costs		Life Cycle Costs	
	Current Total Estimate	Previous Total Estimate	Current Total Estimate	Previous Total Estimate
Operations	3,100	3,100	16,000	16,000
Utilities	2,400	2,400	12,400	12,400
Maintenance & Repair	100	100	600	600
Total	5,600	5,600	29,000	29,000

9. Required D&D Information

	Square Feet
Area of new construction	~25,000
Area of existing facility being replaced and D&D'd by this project	0
Area of other D&D outside the project	0
Area of any additional D&D space to meet the "one-for-one" requirement taken from the banked area.	~25,000

The one-for-one replacement has been met through banked space. A waiver from the one-for-one requirement to eliminate excess space at Fermilab to offset the Mu2e project was approved by DOE Headquarters on November 12, 2009. The waiver identified and transferred to Fermilab 575,104 square feet of excess space to accommodate the new Mu2e facilities and other as yet unbuilt facilities from space that was banked at other DOE facilities.

10. Acquisition Approach

The acquisition approach is fully documented in the Acquisition Strategy approved as part of CD-1. This is a high-level summary of material from that document.

DOE awarded the prime contract for the Mu2e project to the Fermi Research Alliance (FRA), the Fermilab Management and Operating (M&O) contractor, rather than have the DOE compete a contract for fabrication to a third party. FRA has a strong relationship with the high energy physics community and its leadership, including many Fermilab scientists and engineers. This arrangement will facilitate close cooperation and coordination between the Mu2e scientific collaboration and an experienced team of project leaders managed by FRA, which will have primary responsibility for oversight of all subcontracts required to execute the project. These subcontracts are expected to include the purchase of components from third party vendors as well as subcontracts with university groups to fabricate detector subsystems.

The largest procurements are the magnet systems and the civil construction. The superconducting solenoid magnets are divided into three systems that could be procured independently but which must ultimately perform as a single integrated magnetic system. Two of the systems are similar to systems that have been successfully built in private industry, so the engineering design and fabrication for two of the solenoids was subcontracted to a third party vendor after a study of industrial vendor capabilities confirmed that the technical risks were acceptable. The third solenoid is unique because of its rather large size and unusual configuration, and no good industrial analog exists. This solenoid was designed at Fermilab and is being fabricated by a third-party vendor in multiple modular components, each of which is well matched to existing industrial capabilities.

There were two major subcontracts for the civil construction. An architectural and engineering contract was placed on a firm-fixed-price basis for Preliminary (Title I) Design, and Final (Title II) Design with an option for construction support (Title III). The general construction subcontract was placed on a firm-fixed-price basis and was completed successfully.

All subcontracts have been competitively bid and awarded based on best value to the government. Fermi Site Office provides contract oversight for FRA's plans and performance. Project performance metrics for FRA are included in the M&O contractor's annual performance evaluation and measurement plan.